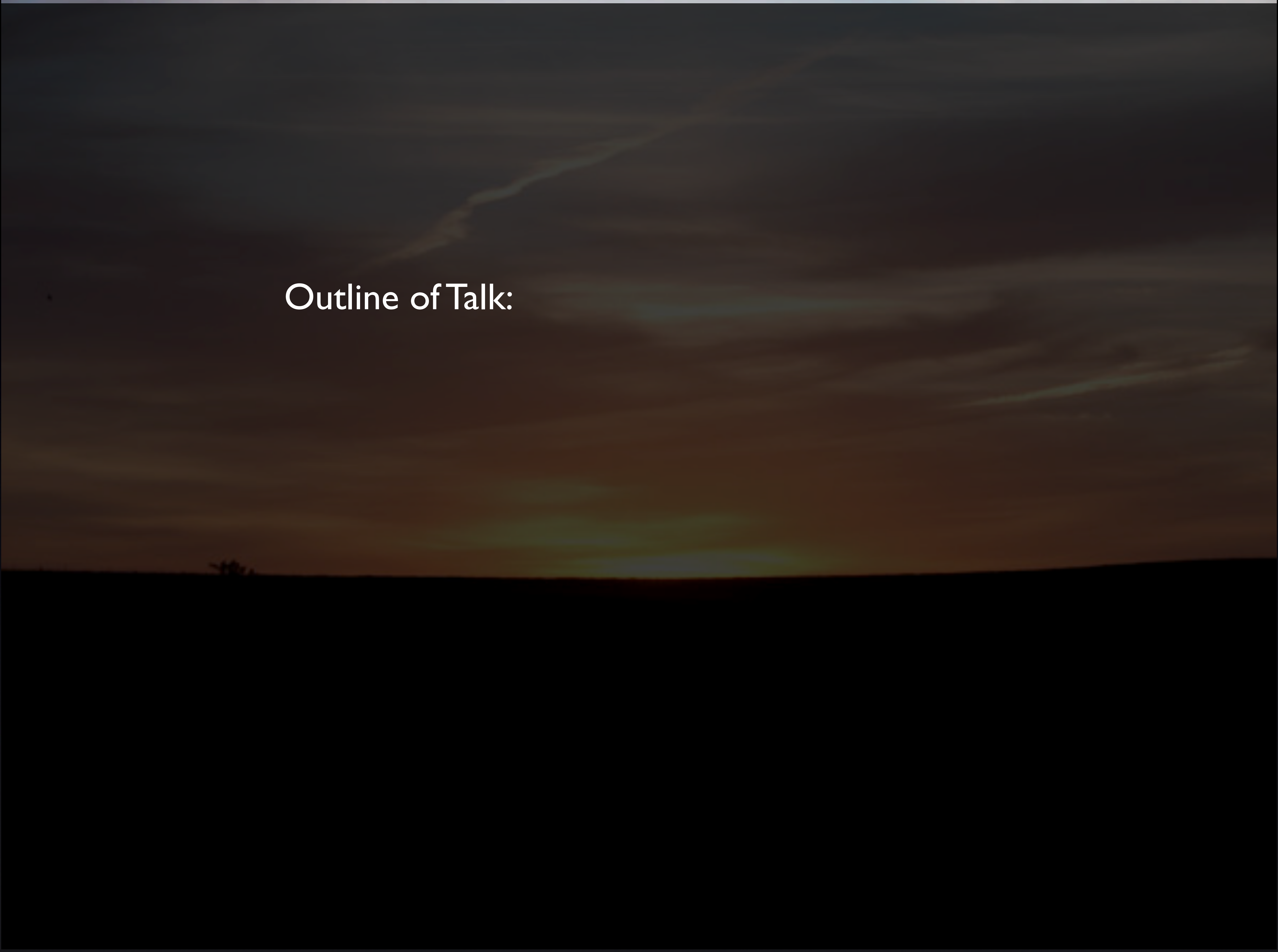
Twilight

Results from the 3rd and Final Phase of the SNO Experiment

J.A. Formaggio
MIT

Fermilab Wine & Cheese
July. 18th, 2008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- Neutrinos, oscillations, and solar physics
- The SNO experiment
- Experimental details of the final phase...
- Results and future horizons....

The First Crack of the Standard Model

- Neutrino oscillation experiments carried out over the last forty years have revealed that neutrinos do possess a small and finite mass, providing the first contradiction in the Standard Model.
- Questions remain: what can we learn from neutrino oscillations and from neutrino masses?

Implications of Neutrino Mass

- Why is the neutrino mass so small compared to the other particles?

- Perhaps neutrinos hold a clue to theories beyond the Standard Model.

- For example, a number of Grand Unified Theories {Left-Right Symmetric; SO(10)} predict the smallness of neutrino mass is related to physics that take place at the unification level.

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The See-Saw Mechanism

$$\mathcal{L} = (\bar{\phi}_L \ \bar{\phi}_R)\mathcal{M}\begin{pmatrix} \phi_L \\ \phi_R \end{pmatrix} \qquad \mathcal{M} = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

$$m_R \sim m_{\mathrm{GUT}}$$

$$m_\nu \sim \frac{m_D^2}{m_R}$$

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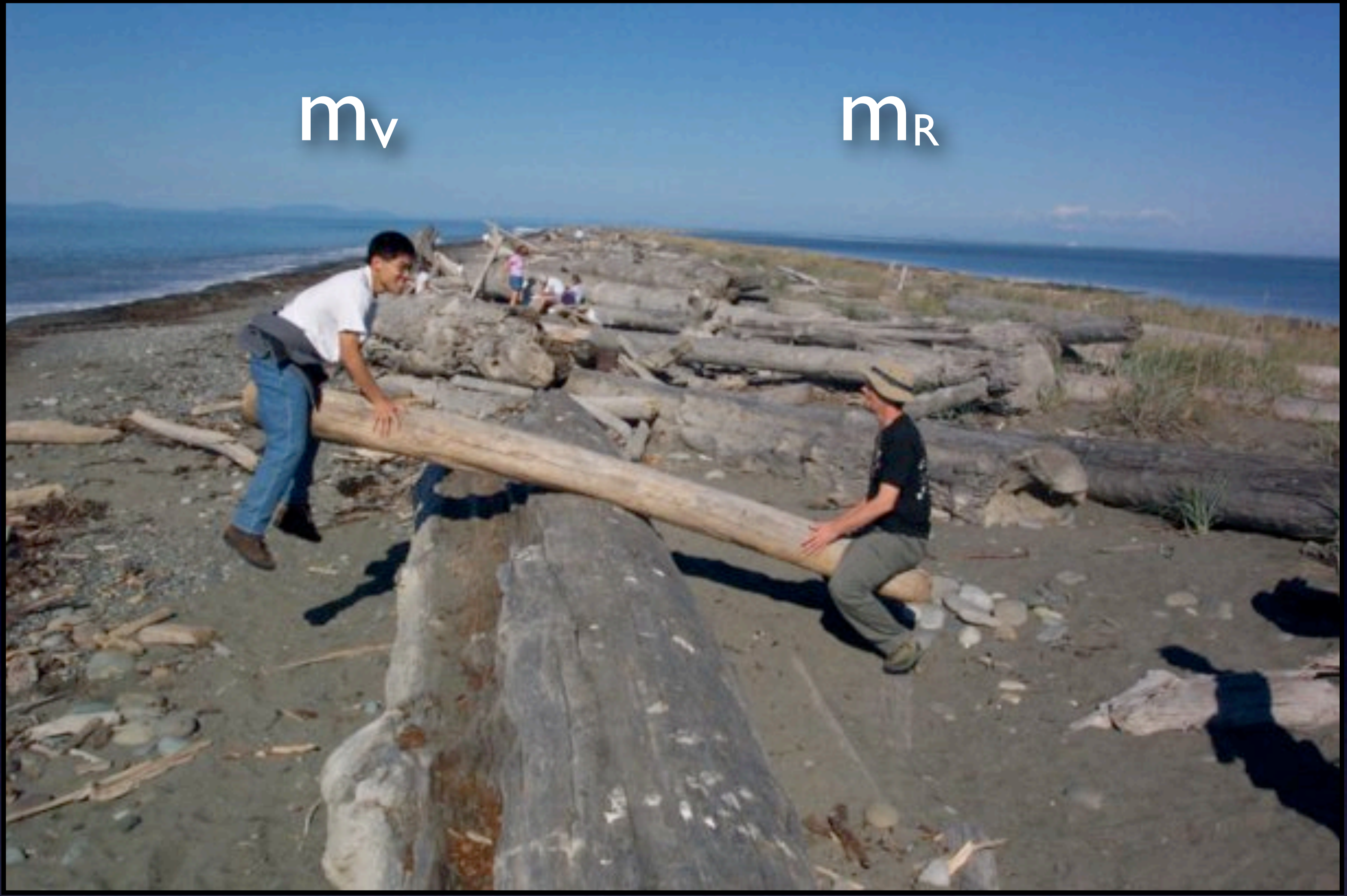

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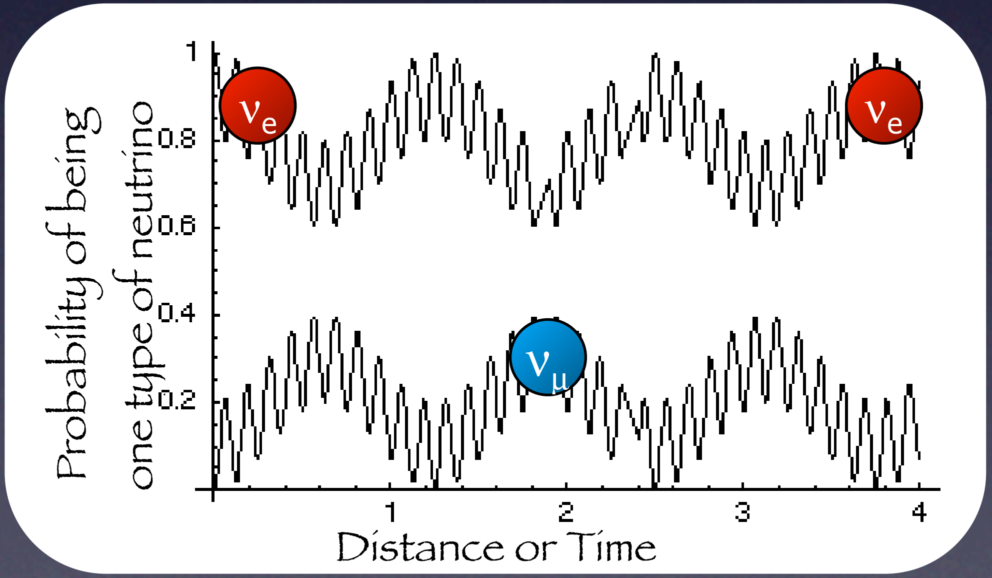
Neutrino Oscillations

- In general, we have a 3 x 3 matrix that describes neutrino mixing (the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP mixing matrix):

- However, the picture simplifies if one of the mixing angles is small...



- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

Bruno Pontecorvo

$$\mathcal{P}_{\rm surv} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4E_\nu} L\right)$$

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$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, long baseline}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

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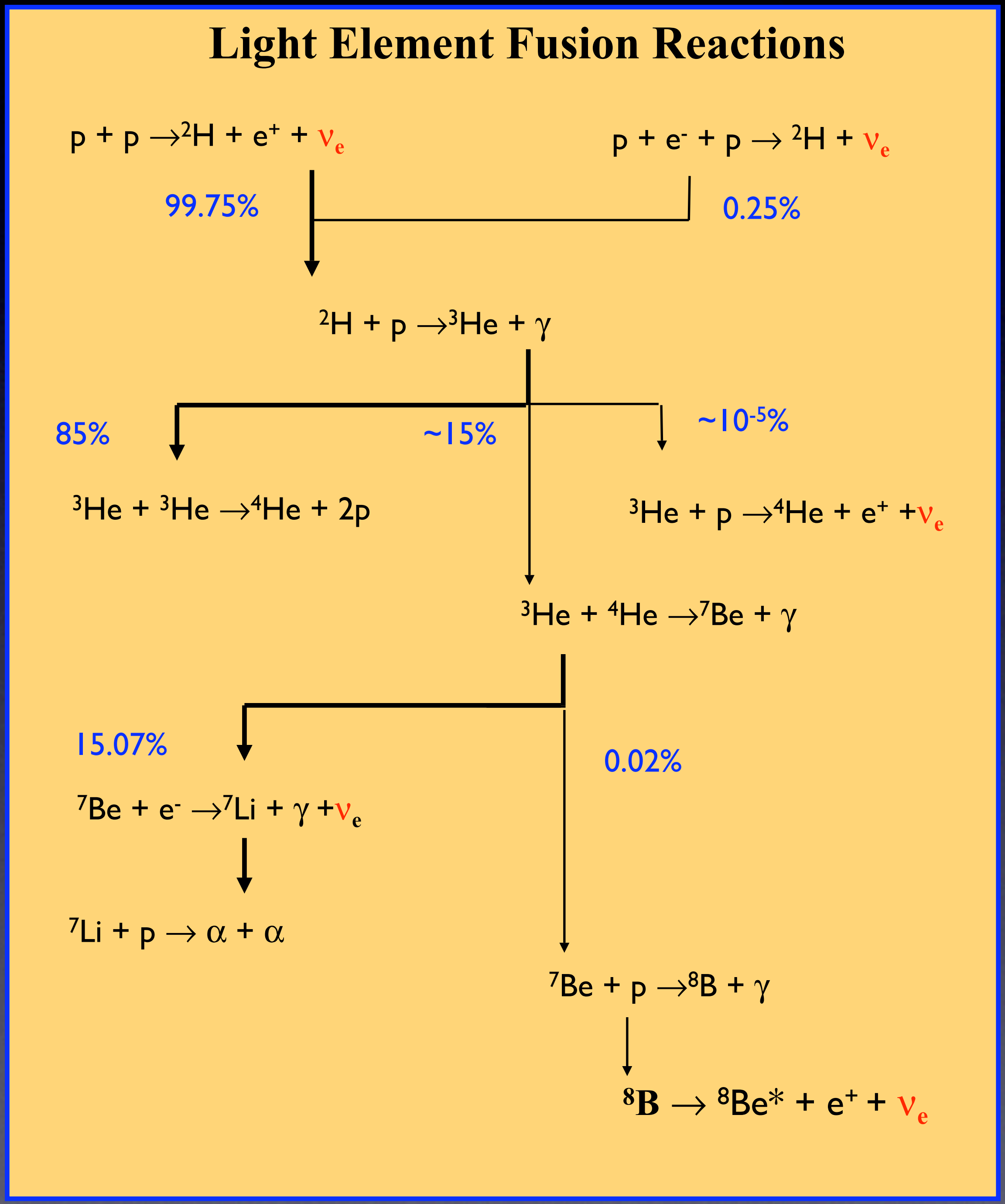
Window into the interior of the sun

- Neutrinos from the sun allow a direct window into the nuclear solar processes.
- Each process has unique neutrino energy spectrum
- Only electron neutrinos are produced at these energies.
- Different experiments sensitive to different aspects of the spectrum.



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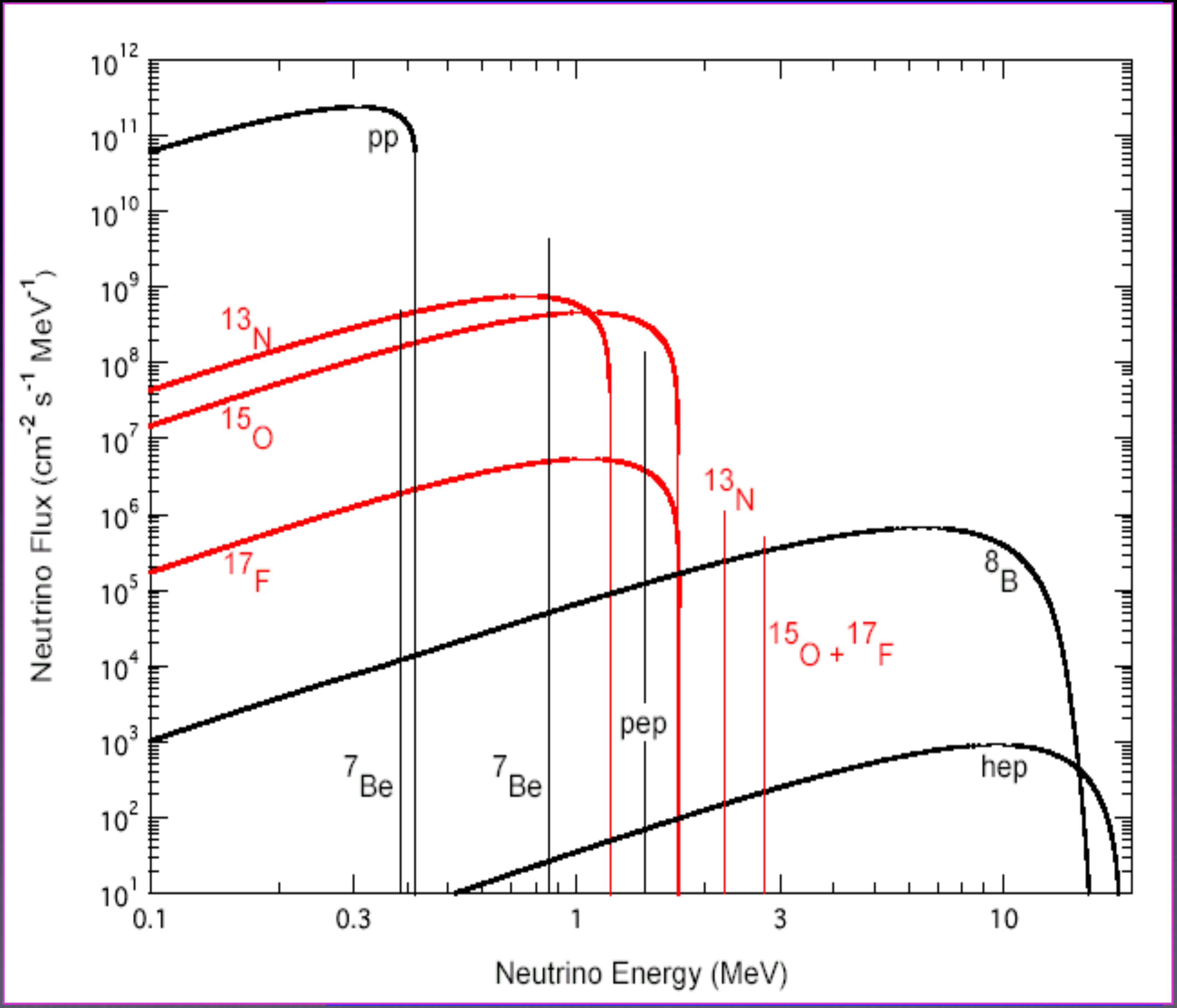

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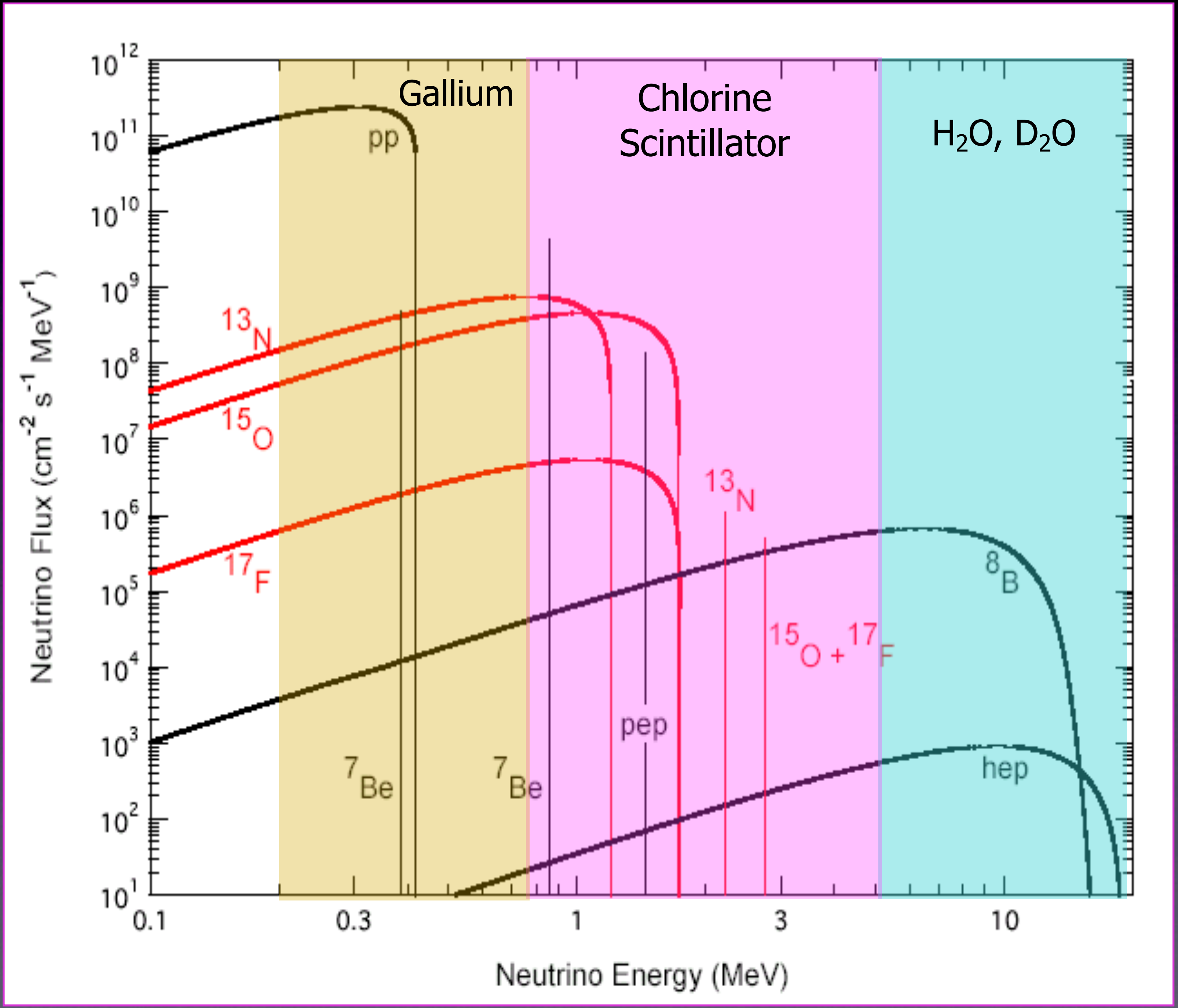
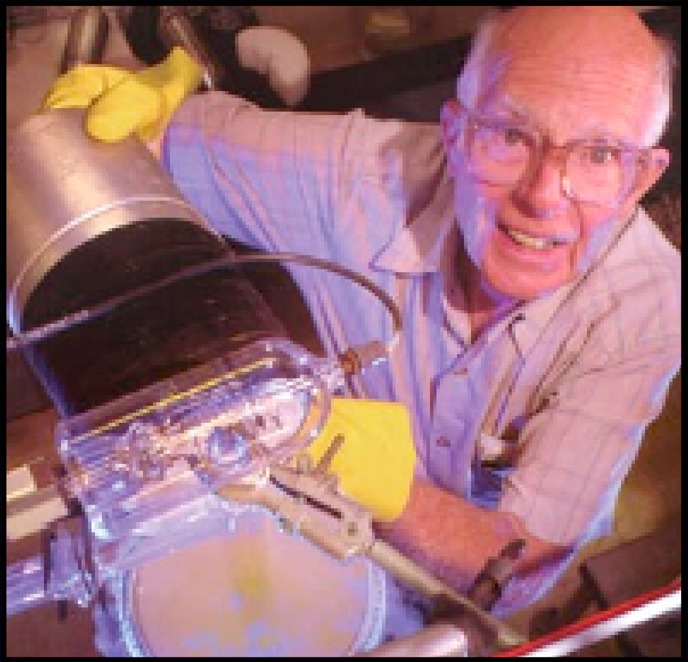


The Solar Puzzle Begins...



Raymond Davis, Jr.
Winner of 2002 Nobel Prize in Physics

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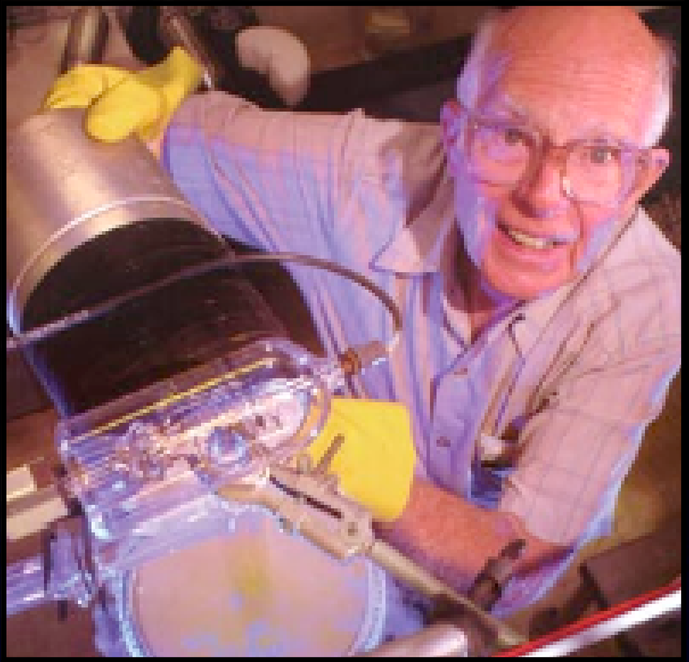

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60s

Ray Davis begins construction of Homestake

Bahcall provides solar flux predictions

Solar puzzle begins

70s

Homestake (^{37}Cl) measurements

MSW mechanism proposed

80s

SAGE (^{71}Ga) begins operations

Helioseismology models compared

90s

GALLEX (^{71}Ga) online

Super-K (H_2O) online

GNO operational

SNO (D_2O) takes data

00s

Solar puzzle SOLVED

Borexino!

1st results from KAMLAND

The SNO Collaboration

- Brookhaven National Laboratory
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- Louisiana State University
- Massachusetts Institute of Technology
- University of Pennsylvania
- University of Texas at Austin
- University of Washington
- University of British Columbia
- Carleton University
- University of Guelph
- Laurentian University
- Queen's University
- TRIUMF
- University of Oxford
- LIP, Lisbon, Portugal

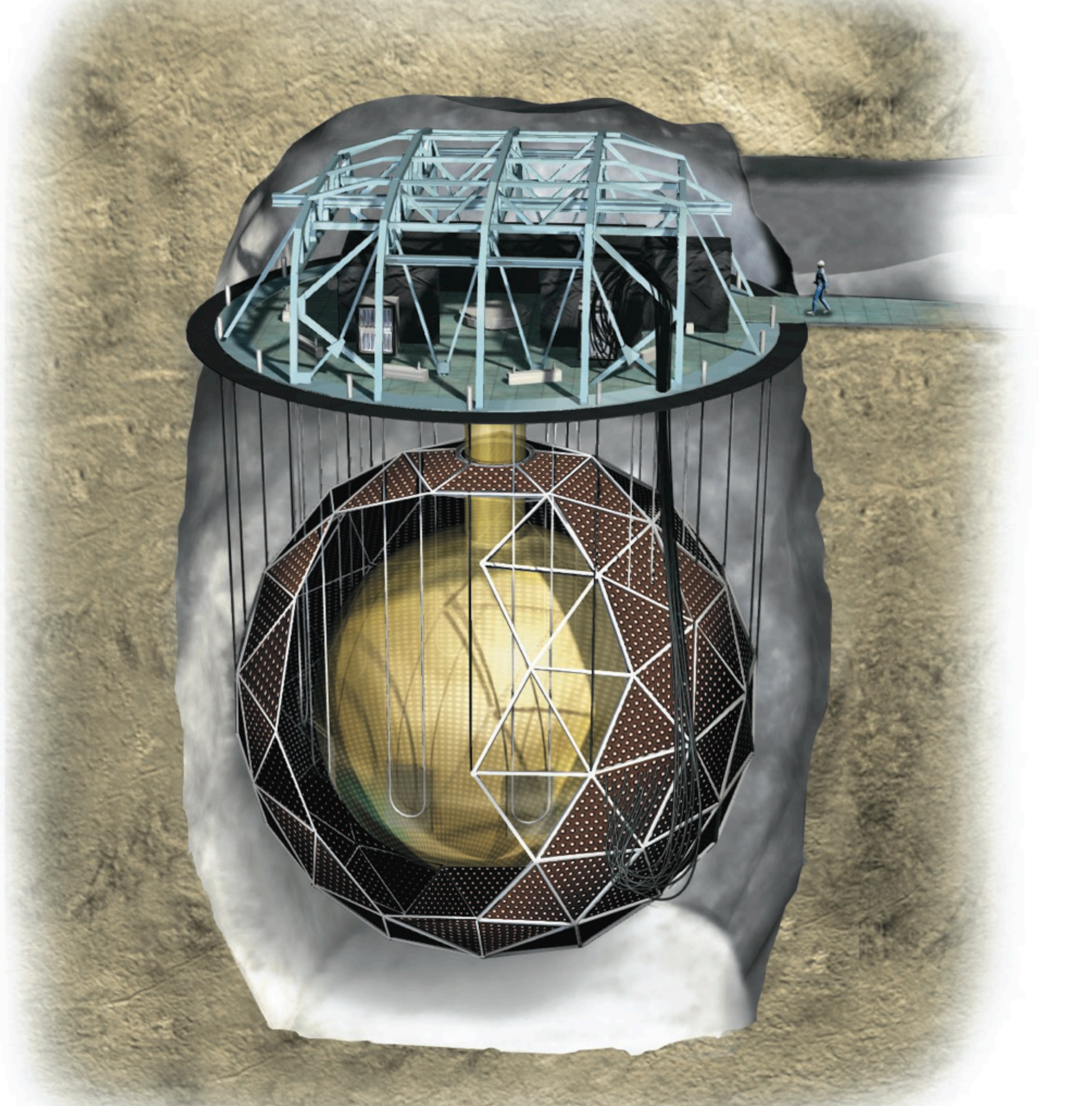

The Sudbury Neutrino
Observatory
(surface view)

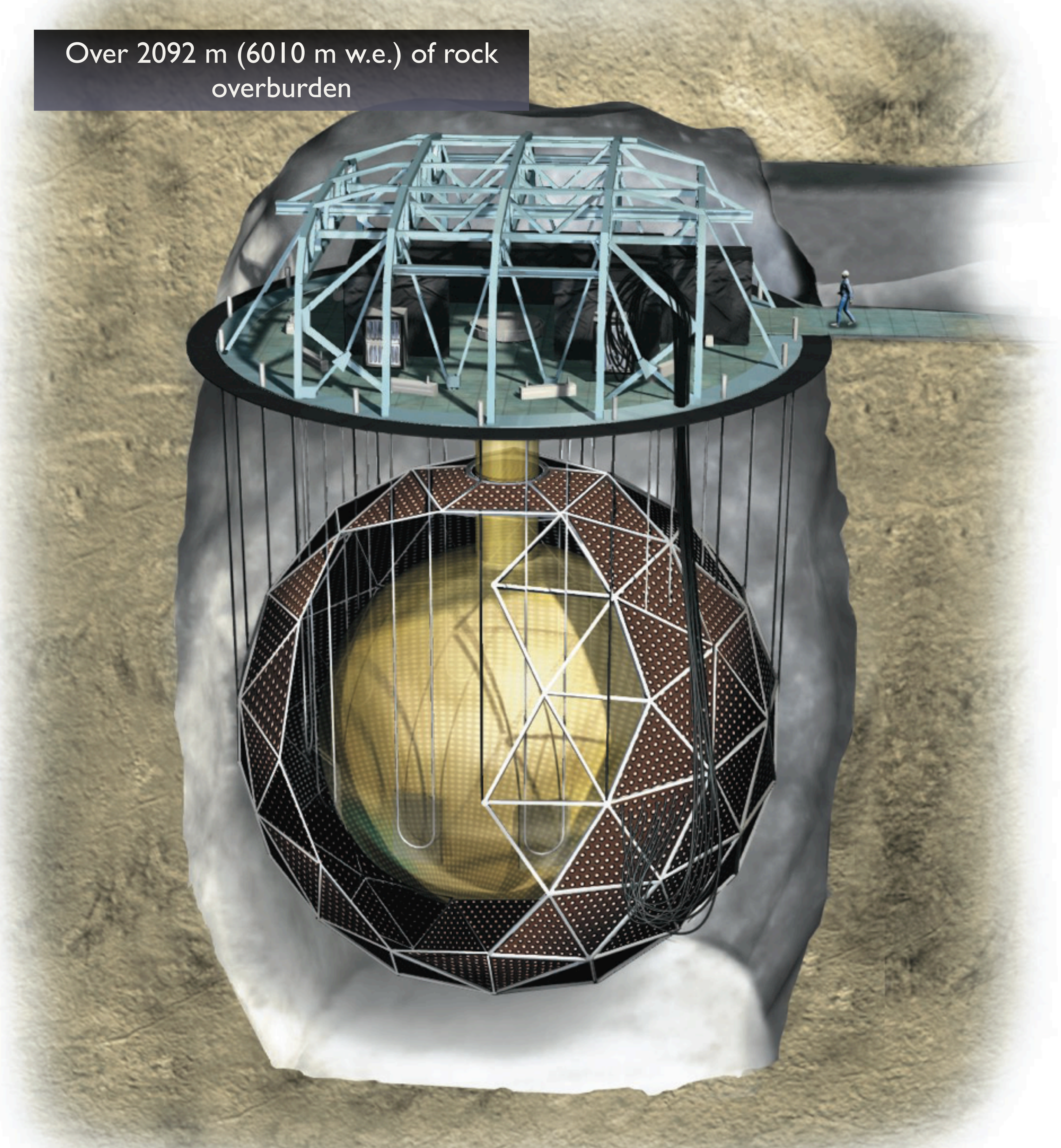

Neutrinos?
The Sudbury Neutrino Observatory (surface view)

The Sudbury

Neutrino

Observatory





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Neutrino

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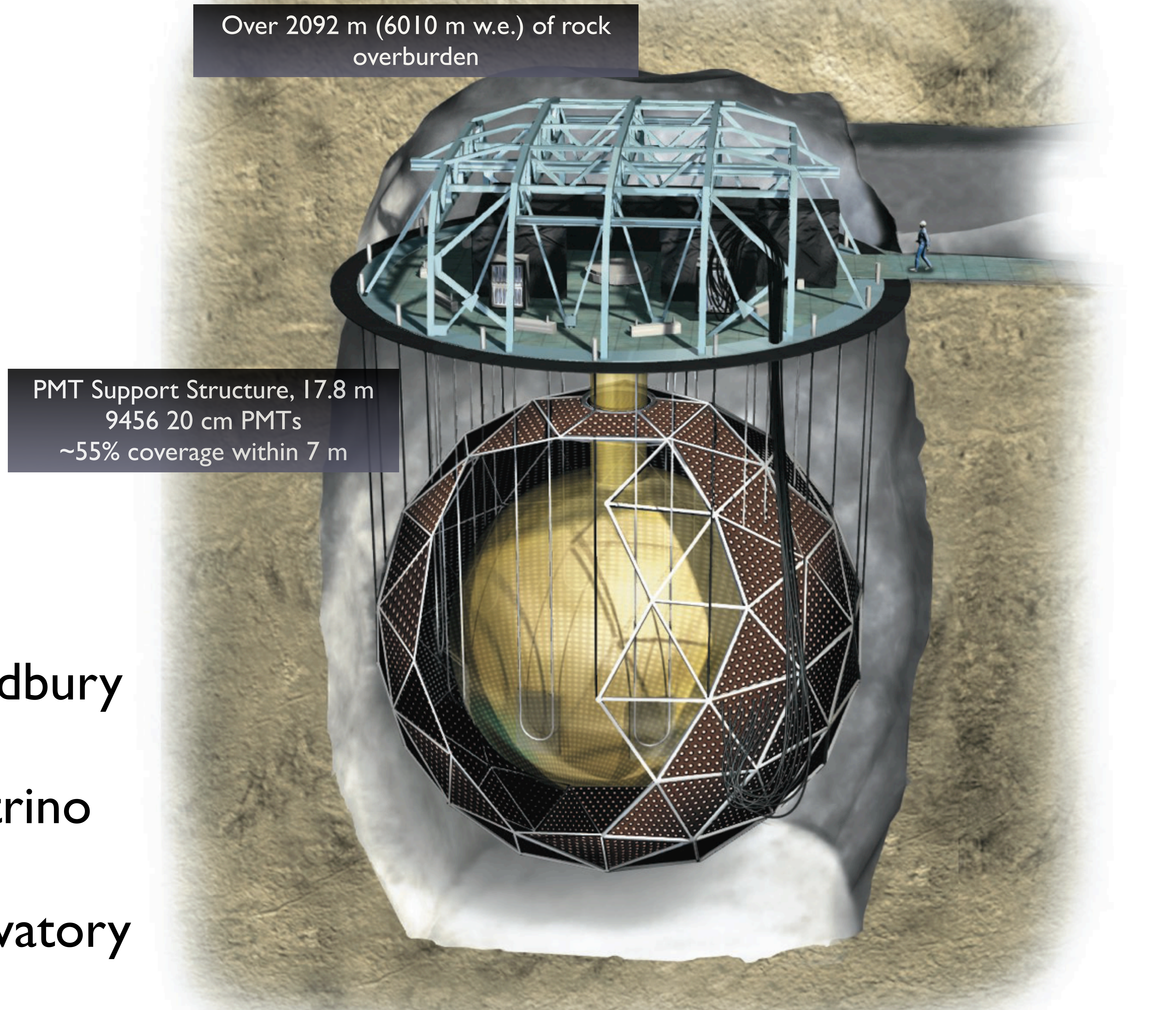

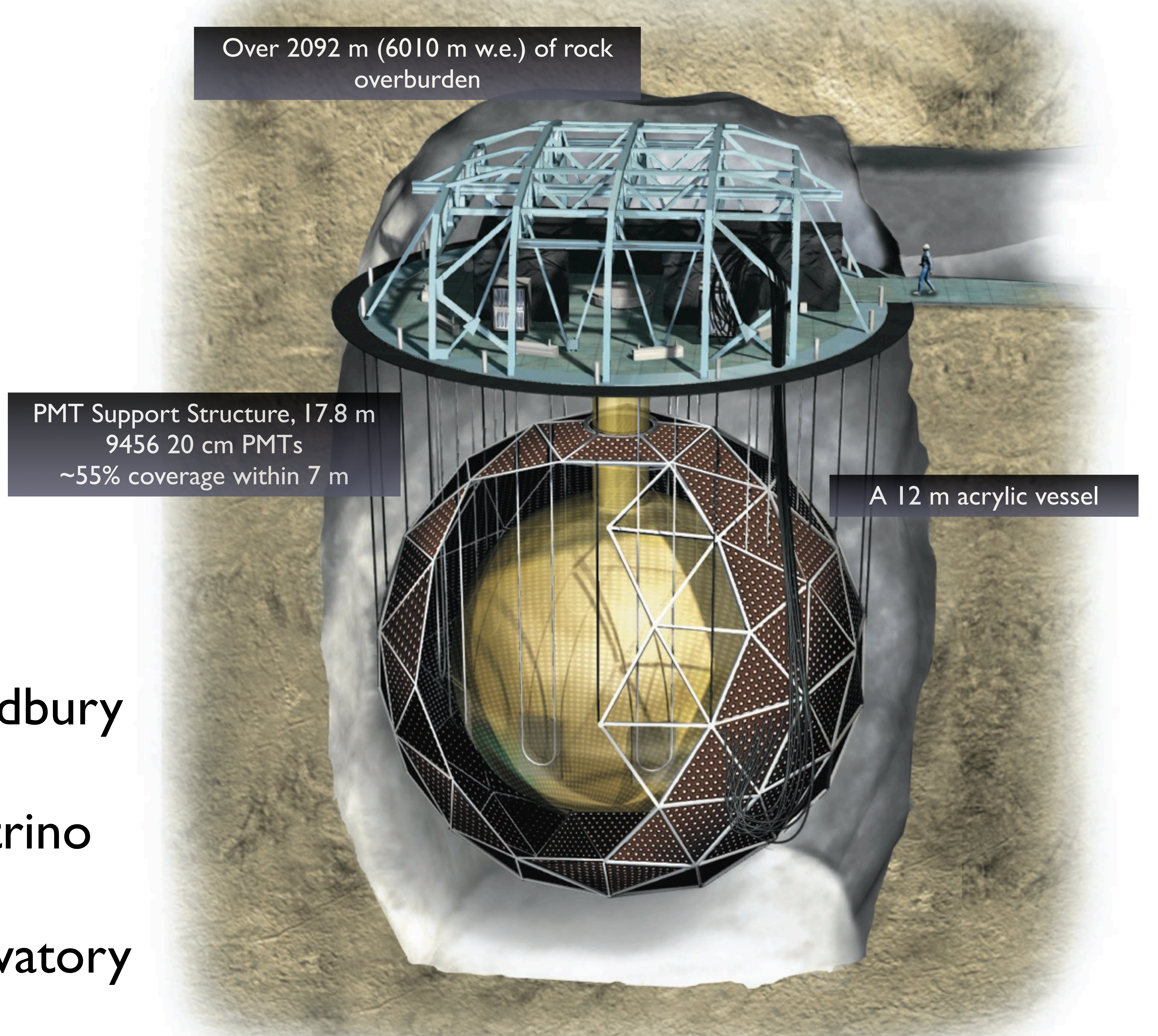

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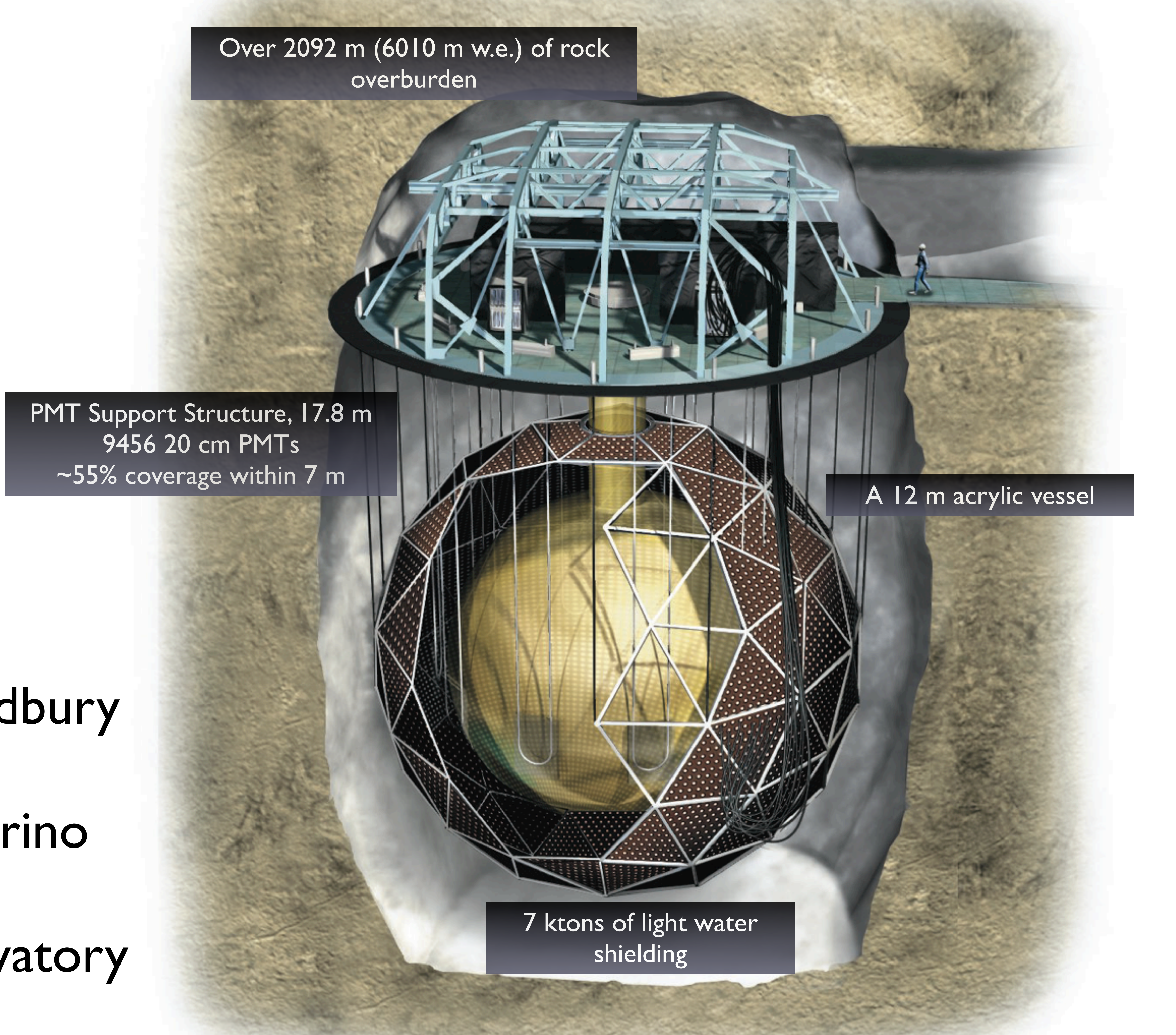

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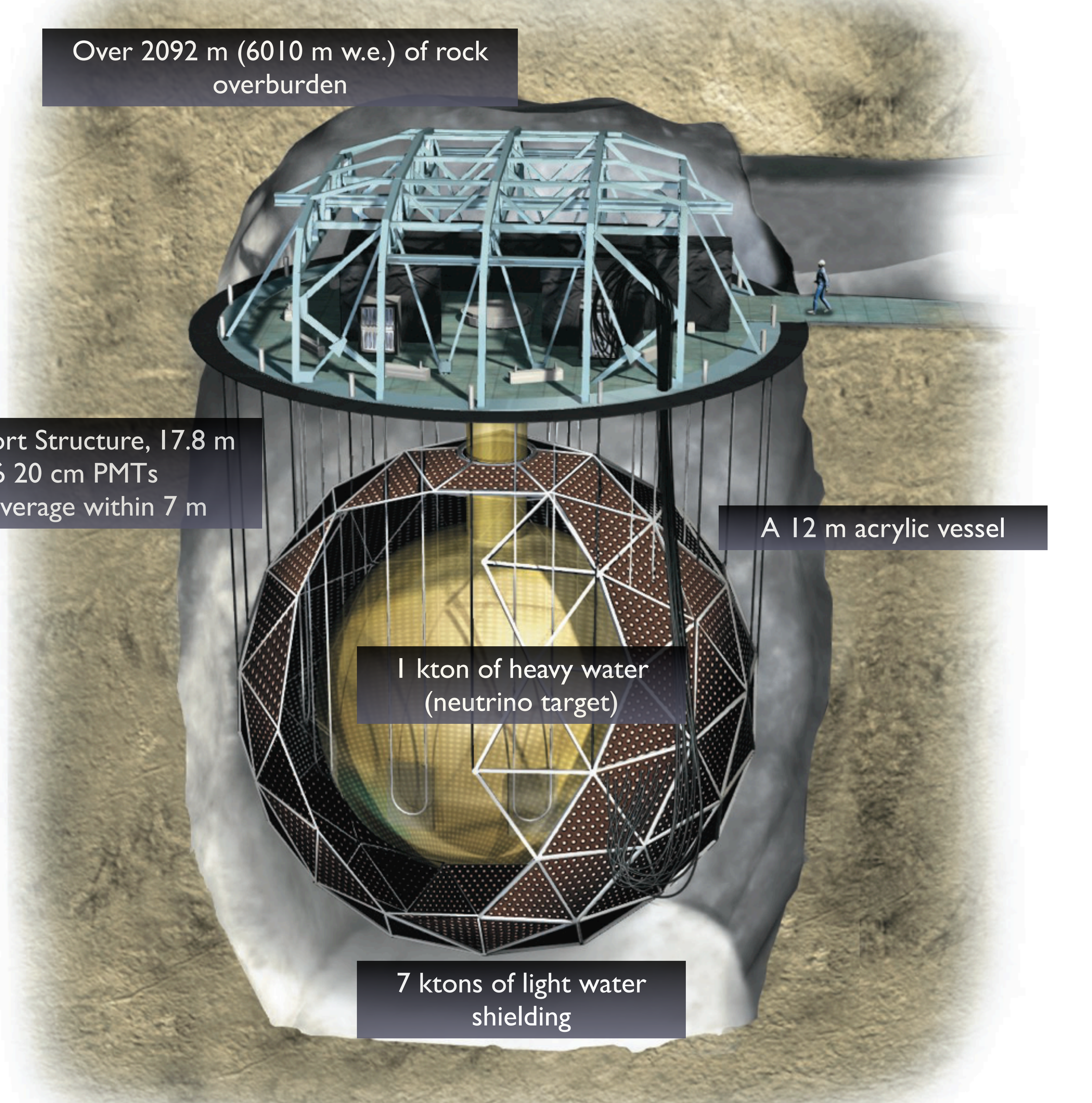

SNO during Construction

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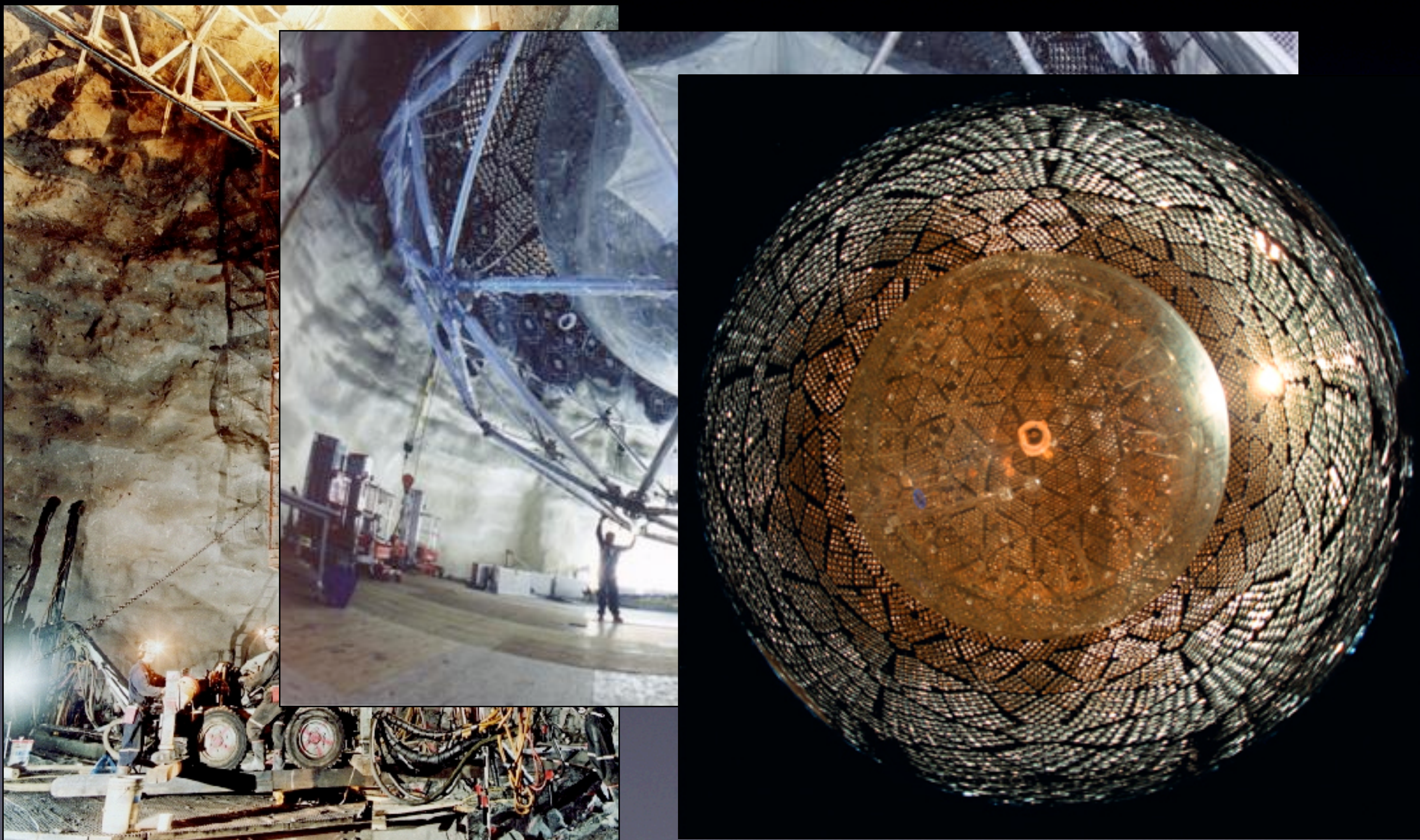

Different Channels
Same Experiment

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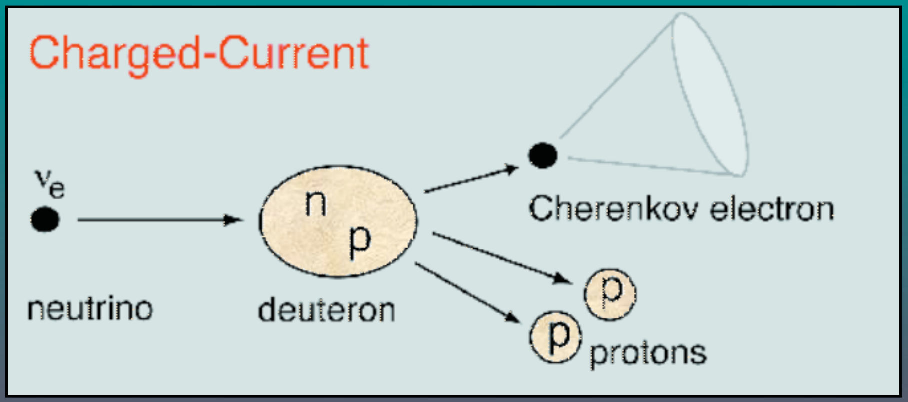
The Charged Current (CC) Interaction:

Signature: Cerenkov ring from ejected electron

Sensitive to ν_e flux only.



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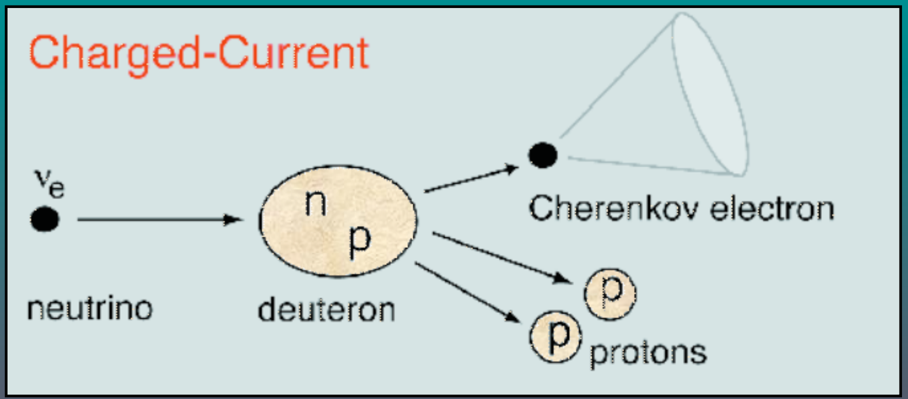

The Neutral Current (NC) Interaction:

Signature: Neutron emitted from deuterium break-up

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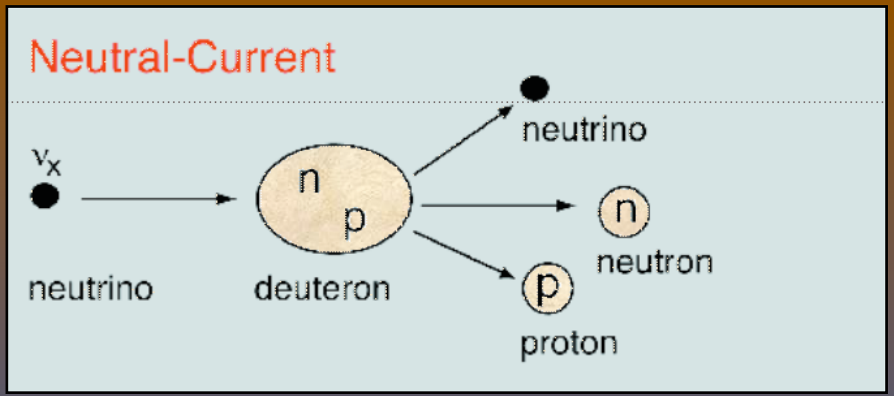

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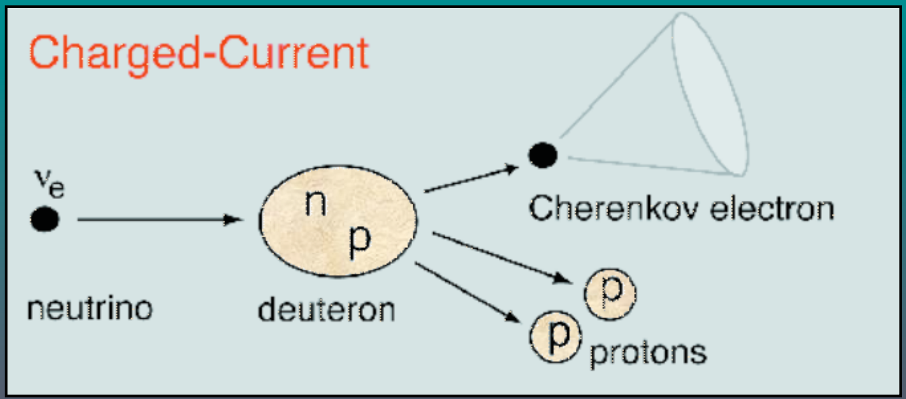

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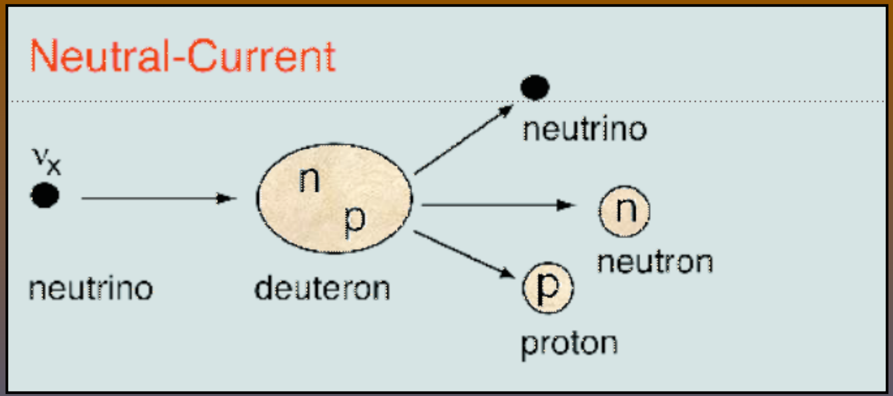
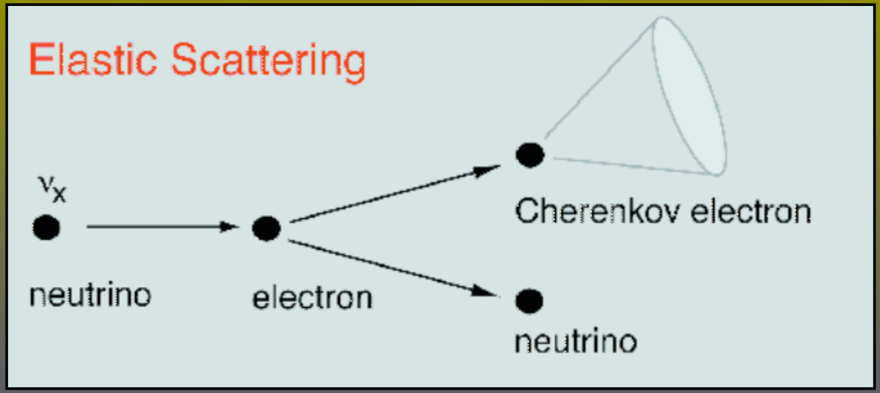


The Elastic Scattering (ES) Interaction:

Signature: Electron with high directional correlation to the sun

Sensitive mainly to ν_e . Some sensitivity to ν_μ, and ν_τ.



The Essence of the Measurement...

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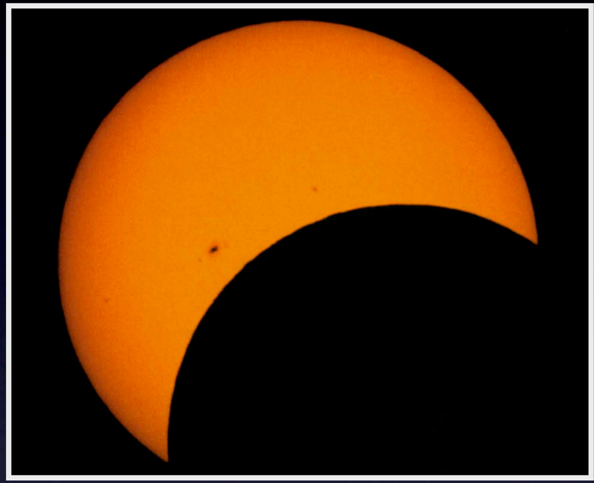

If one looks only
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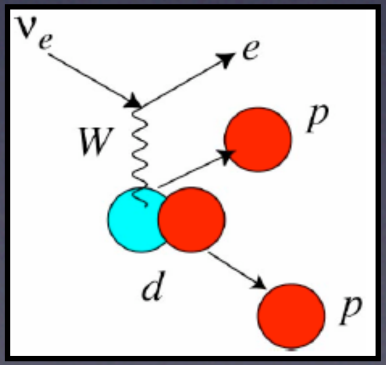

Charged Current

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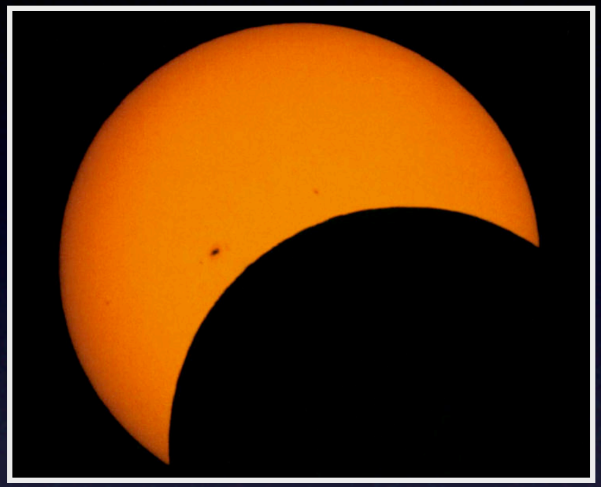

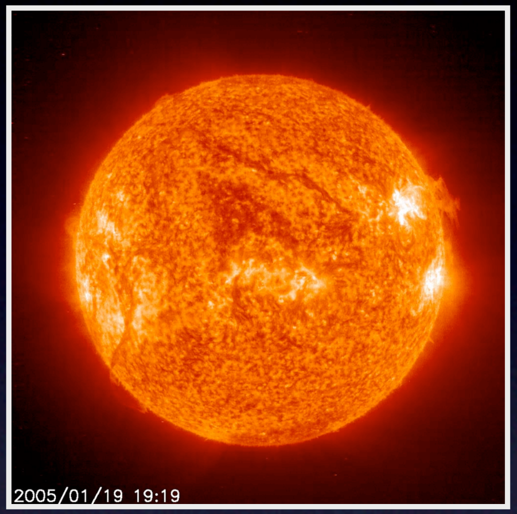

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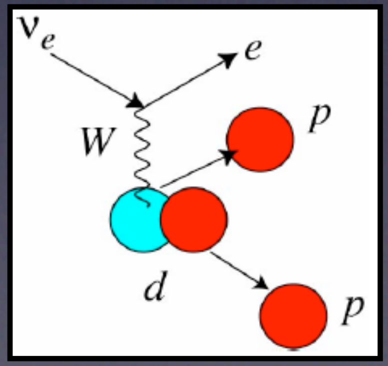

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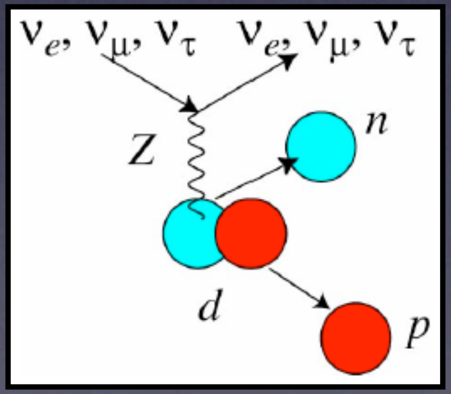
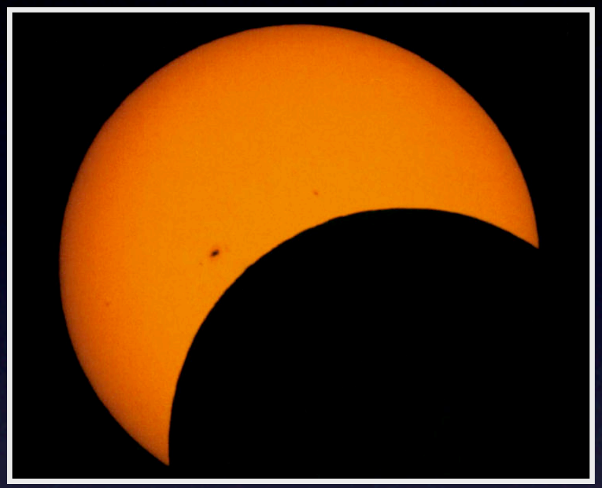


Neutral Current

The Essence of the Measurement...



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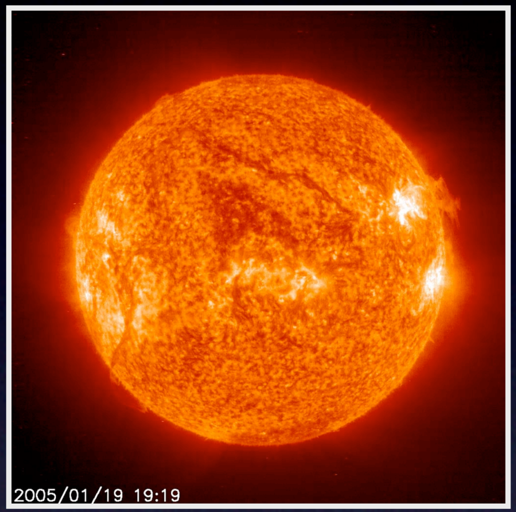

= Oscillations

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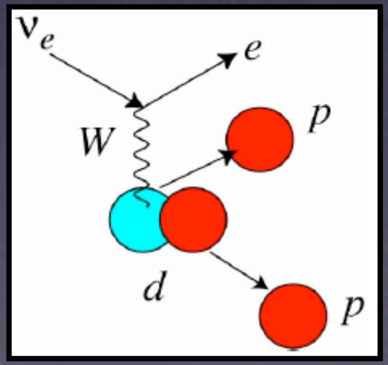

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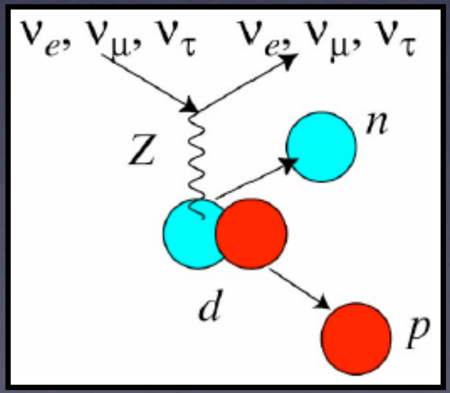

Neutral Current

The Three Phases of SNO...

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D_2O

NC sensitivity

Capture on deuterium

Run from 1999–2001

(304 live days)

$$n + {}^{2}H \rightarrow {}^{3}H + \gamma$$

Separate electron and neutron (photon) using energy, position, and direction.

The Three Phases of SNO...

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Capture on deuterium
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Salt

Enhanced
NC sensitivity

Capture on salt
Run from 2001–2003
(391 live days)

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum\gamma$

Separate electron and neutron (photons) using ring topology.

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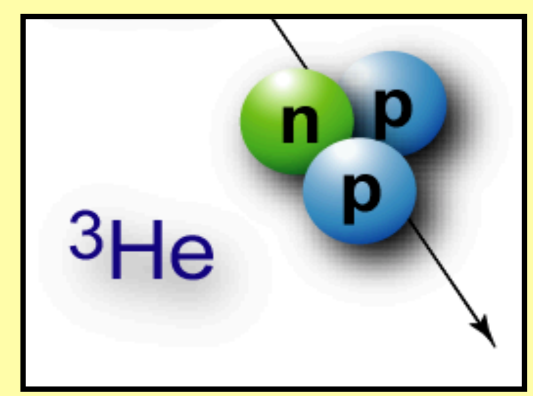
NCD

Neutral Current Detectors

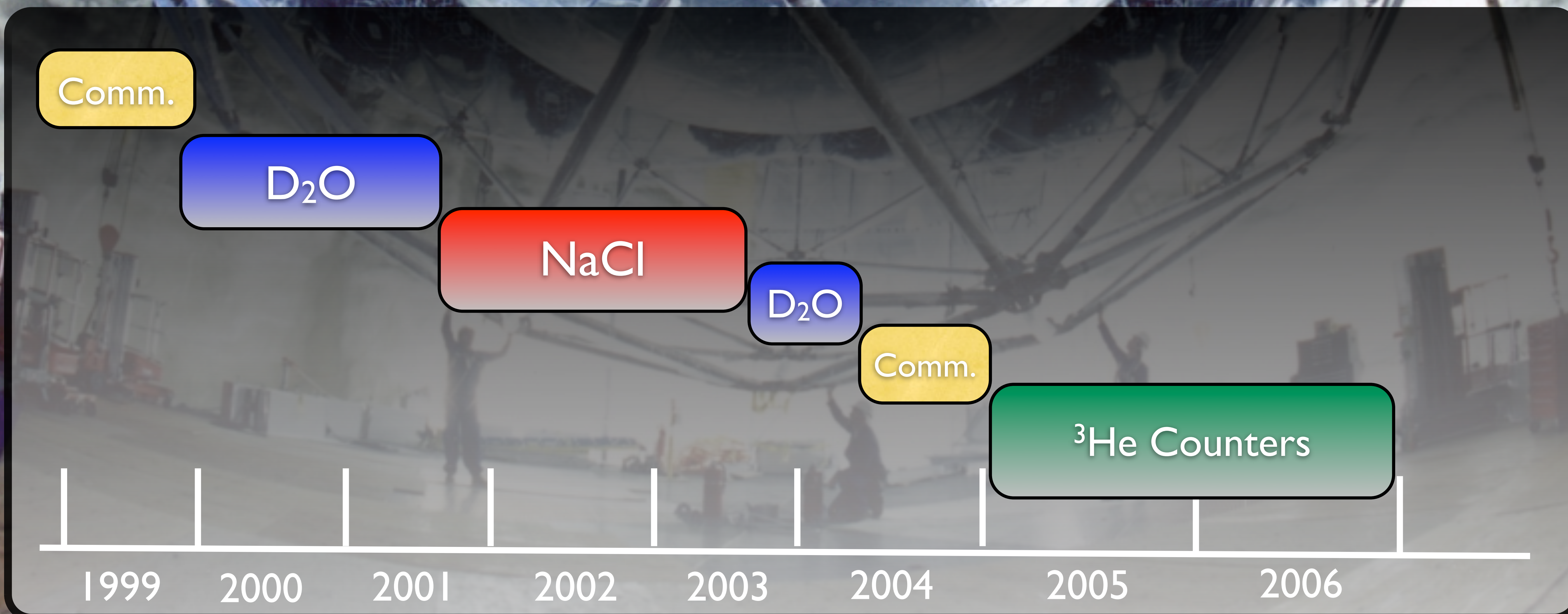
Capture on neutron counters
Run from 2004–2007
(385 live days)

$n + {}^{3}He \rightarrow {}^{3}H + p$



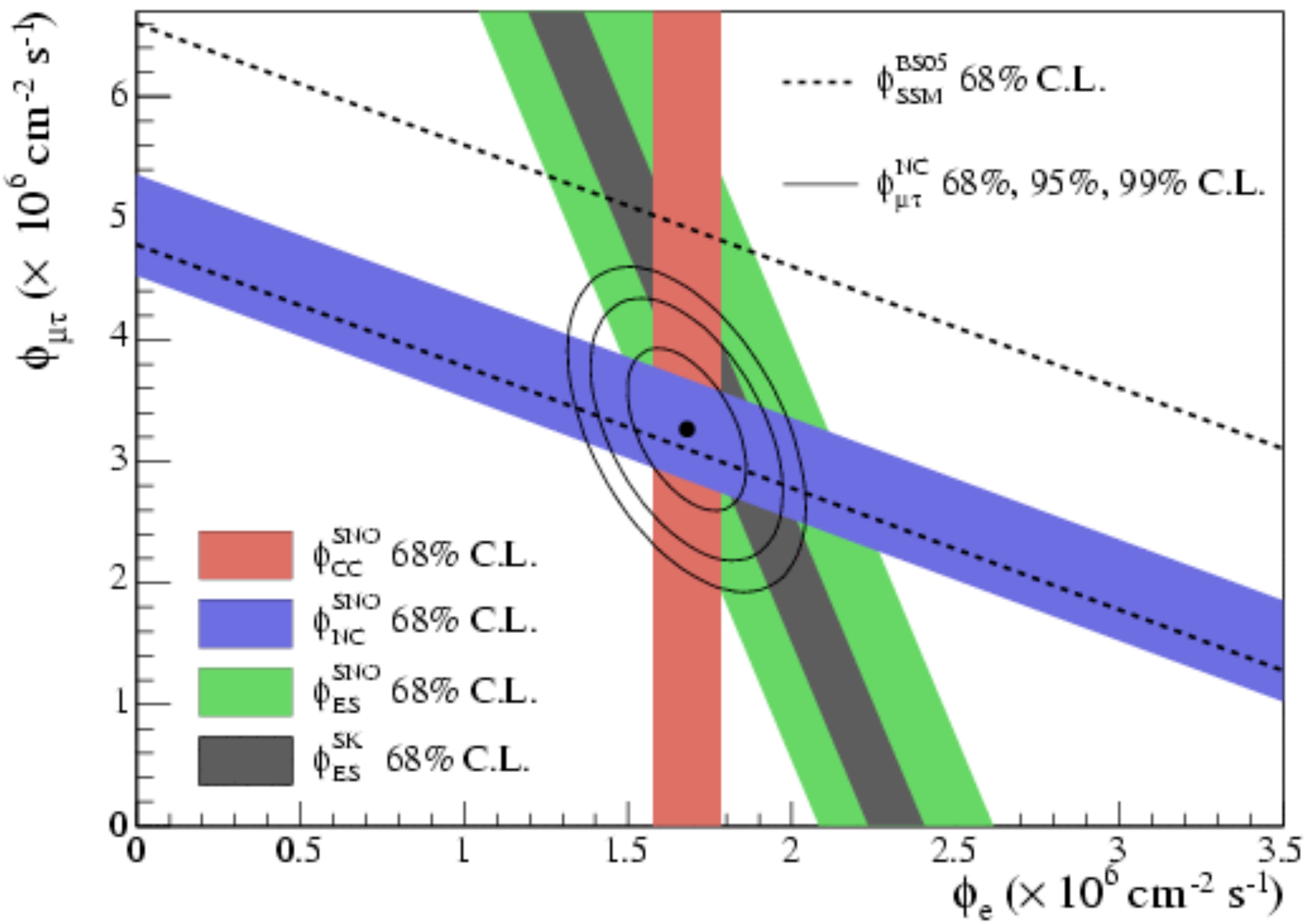
Measure NC rate with entirely *different* detection systems

The Three Phases of SNO...

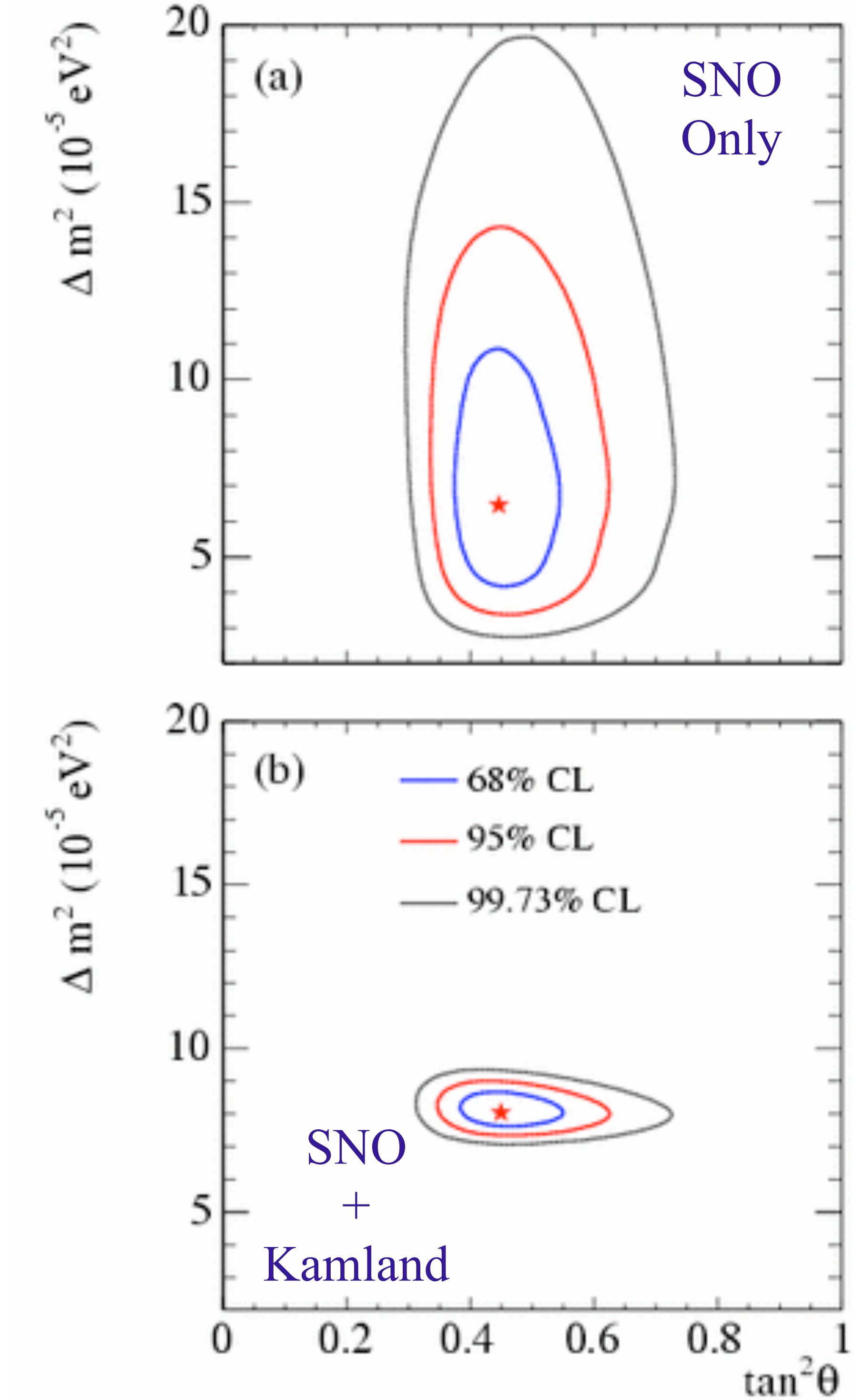


Results from the Salt Phase

$$\frac{\phi_{CC}}{\phi_{NC}} = \mathbf{0.34 \pm 0.023(stat.)^{+0.029}_{-0.031} = \cos^4\theta_{13}\sin^2\theta_{12}}$$



SNO Collaboration, PRC **72**, 055502 (2005)
391 Days of Dissolved Salt Data



Transmuted from discovery to *precision* measurement...

The Why?...

The Why?...

It is natural to consider the answers to fundamental questions?

The critics...

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[In Chess] Why can't a king capture another king?

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Why do orca whales eat penguins?

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The critics...

- Different systematics from previous phases.
- Separate signal paths
- Break correlations between CC and NC signal
- Charged current spectrum no longer contaminated by 6.25 MeV gamma from neutron capture on deuterium

The ^{3}He Proportional Counters

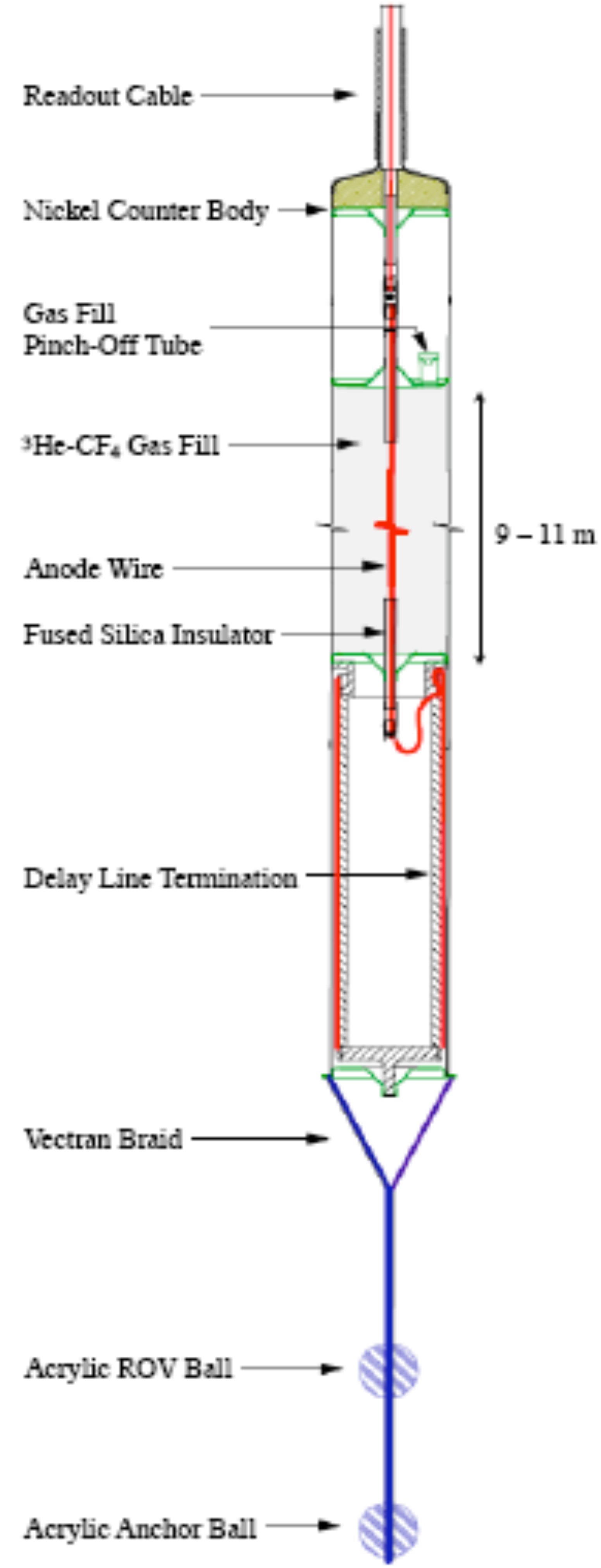
- The neutral current detectors use neutron capture on ^{3}He to independently detect neutrons.

$$n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + p$$

- Each "string" consists of a series of ultra-clean CVD nickel tubes with a single high voltage wire in the center and ^{3}He$^{(85\%)}$:CF_4 $^{(15\%)}$.

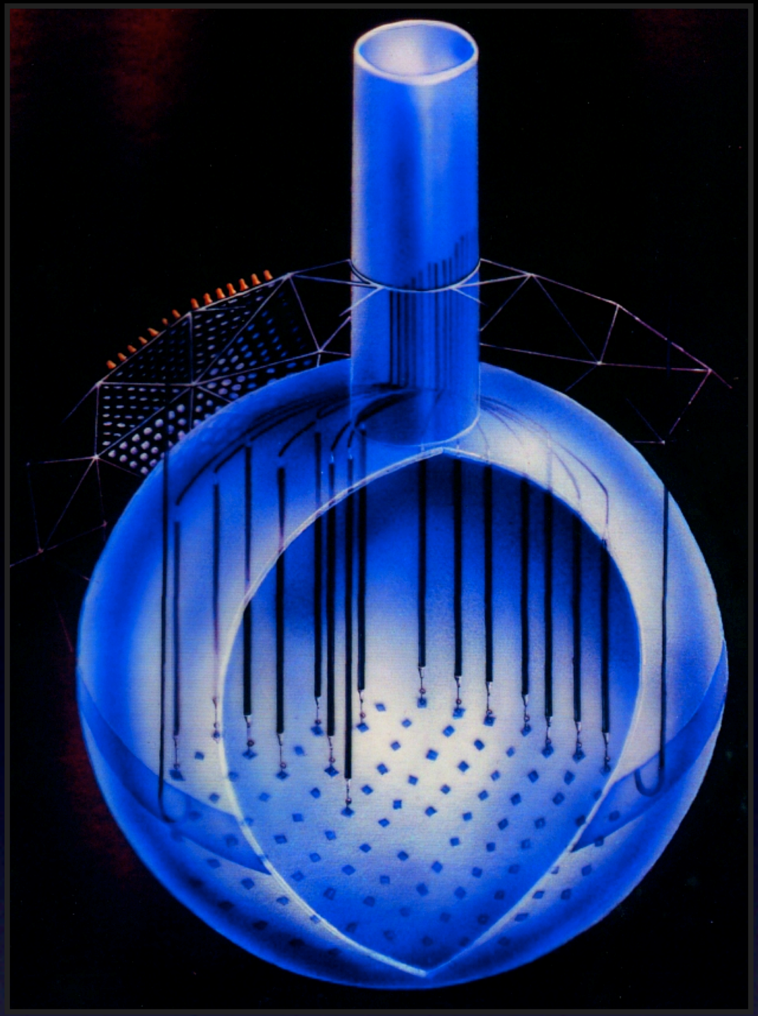
- At present, lowest alpha rate from previous counters (x 100 cleaner)

$$\mathrm{gTh/gNCD} = 3.43^{+1.49}_{-2.11} \times 10^{-12}$$
$$\mathrm{gU/gNCD} = 1.81^{+0.80}_{-1.12} \times 10^{-12}$$

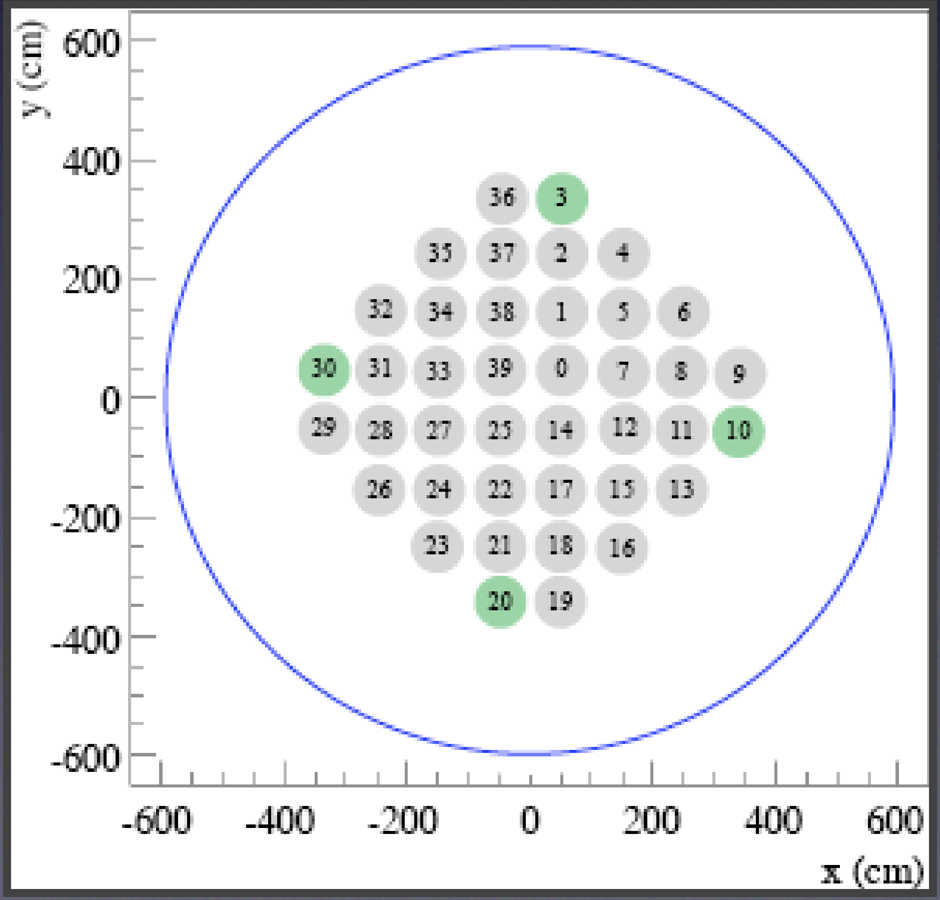


The Array and its Deployment

- Full array consists of 36 ^{3}He strings (for signal) and 4 ^{4}He strings (for background studies).
- Arranged in 1 x 1 m grid with a total length of 398 meters.
- Configured so as to provide maximum signal with minimal light occultation (~9% of Cherenkov light blocked).



Array configuration



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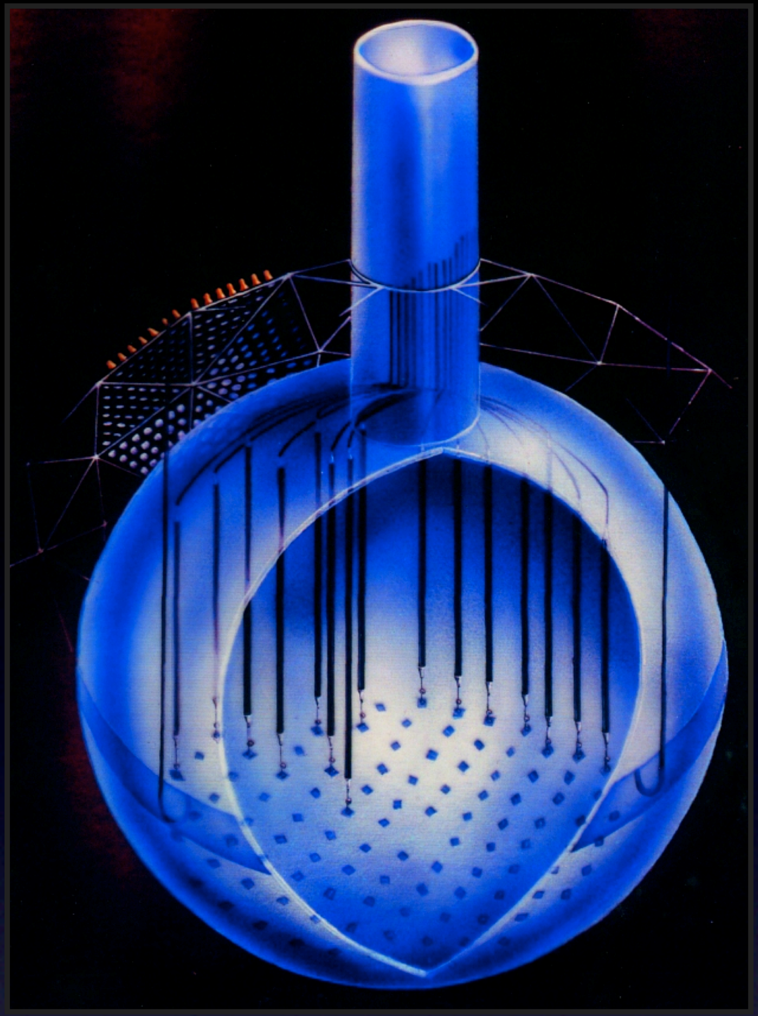

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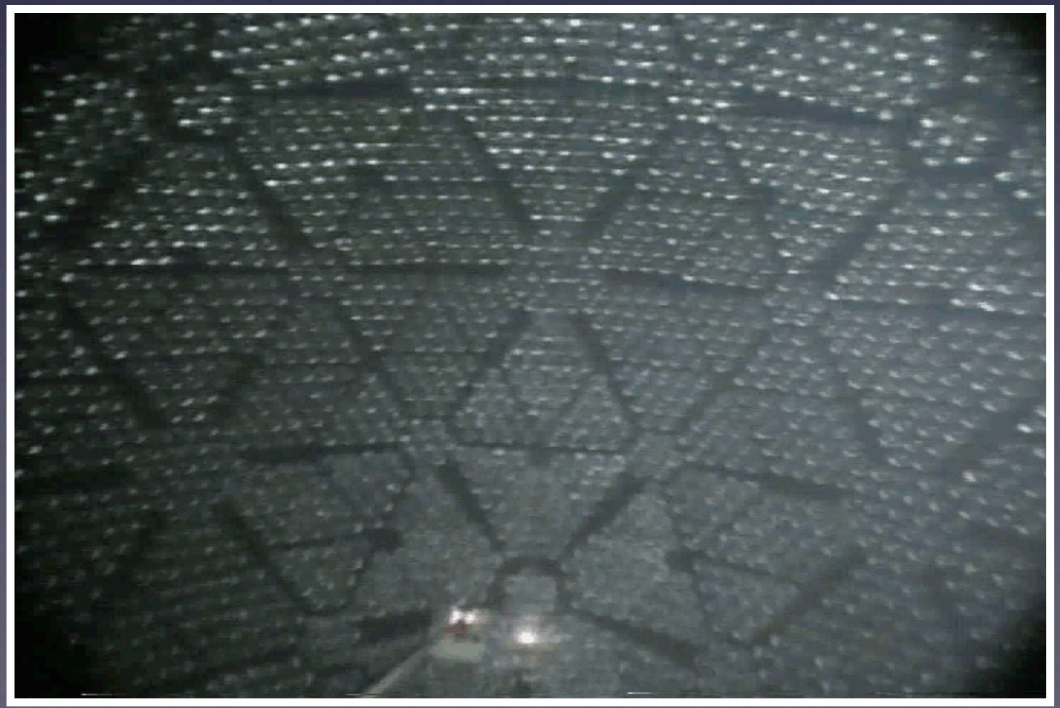
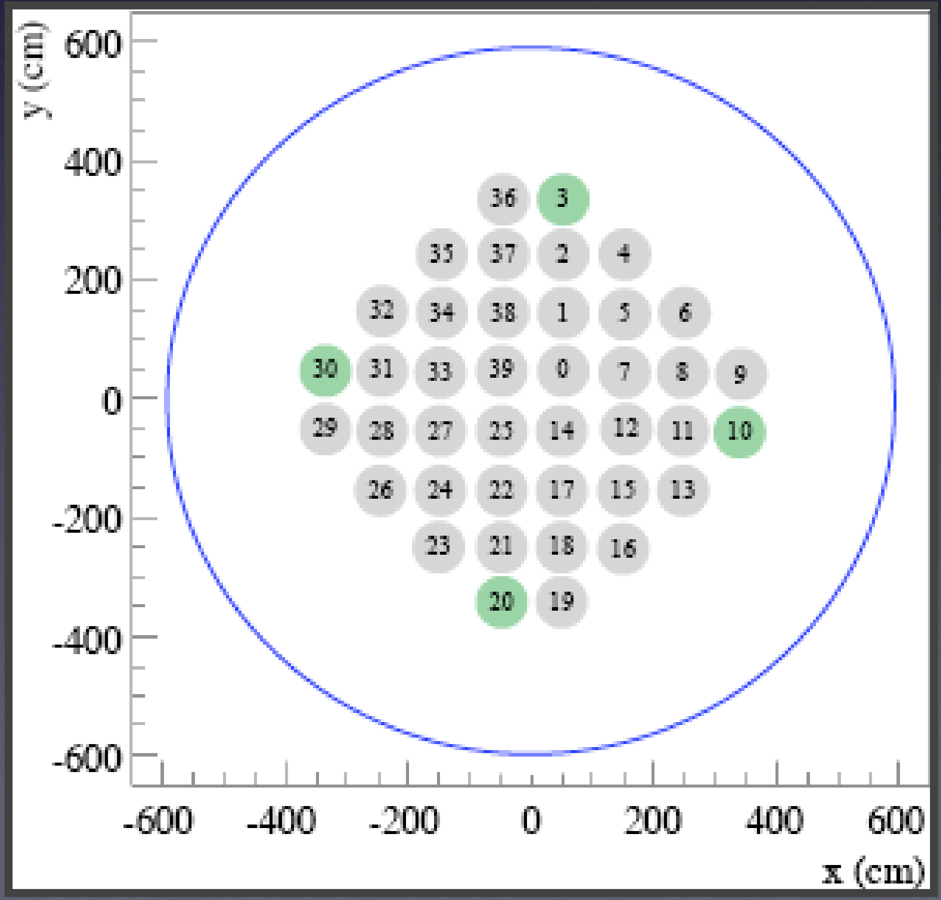
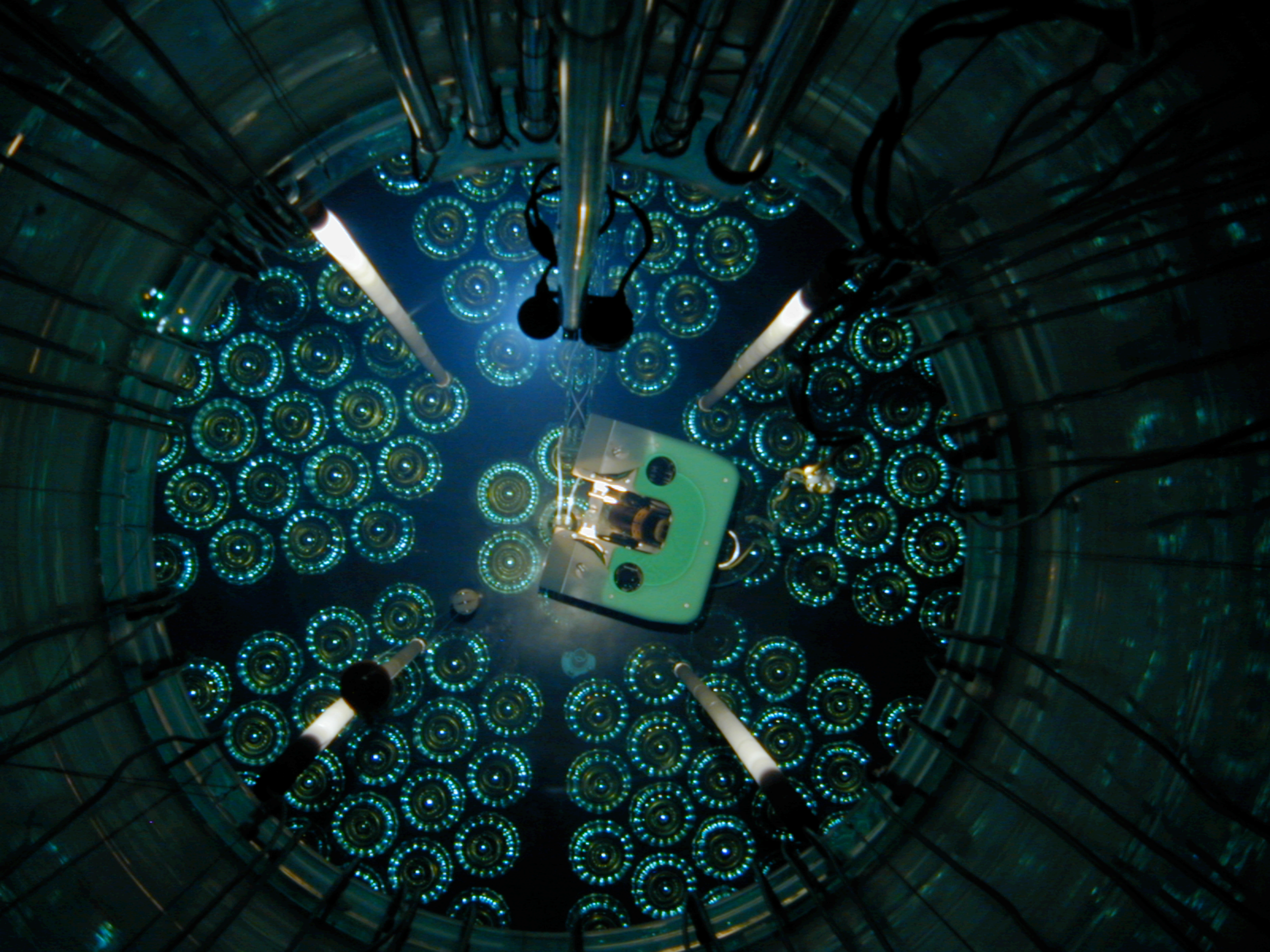


Deployment





The (New) Signal

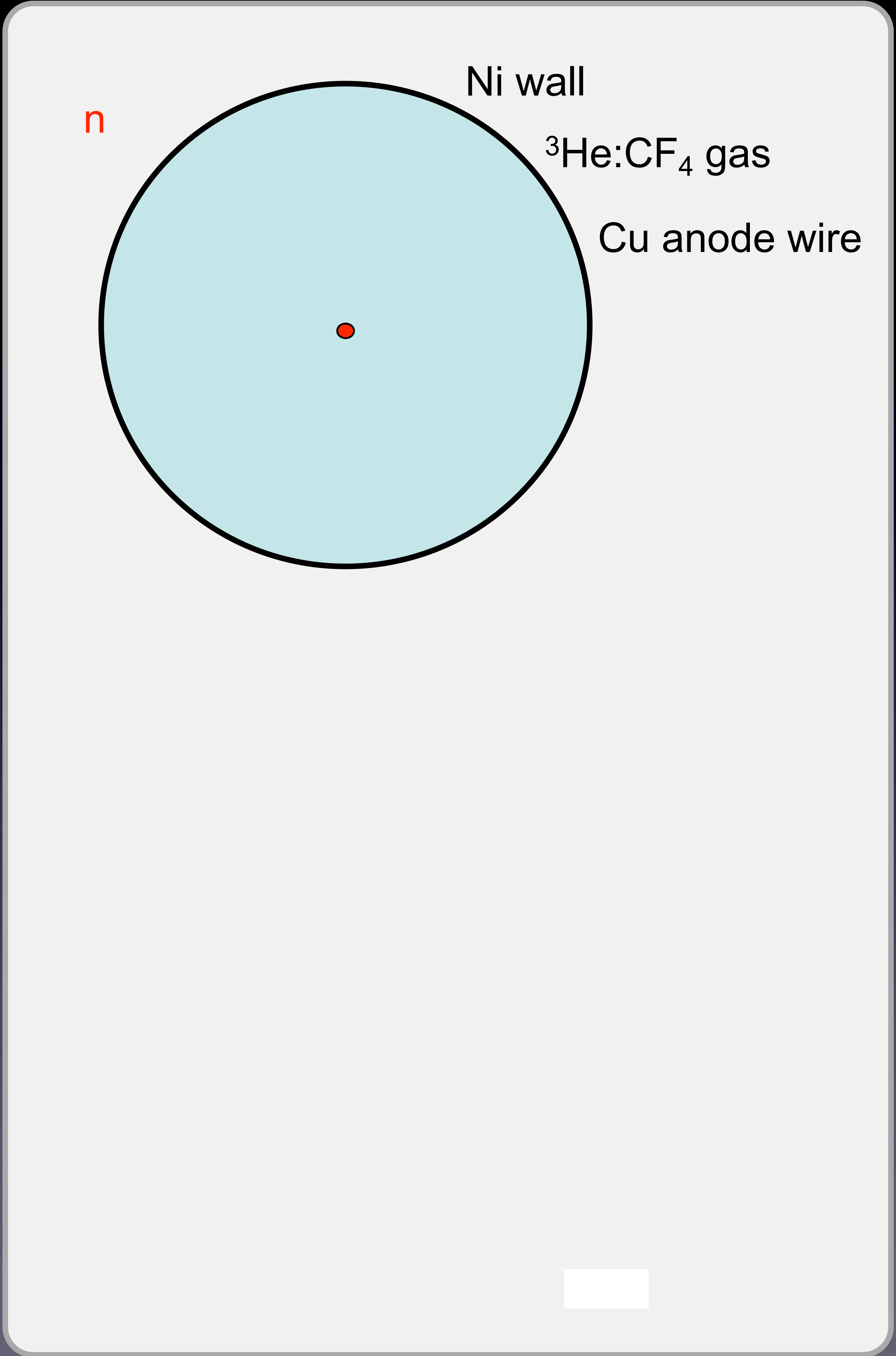
- Proportional counters look at neutron capture on helium for distinct signal.

$$n + {}^3\mathrm{He} \to {}^3\mathrm{H} + p$$

- Main peak stems from full energy deposition.

- Shoulders at 191 keV and 573 keV from triton or proton striking the nickel wall.

- Must also consider alpha energy deposition from walls, wire, and bulk (gas).



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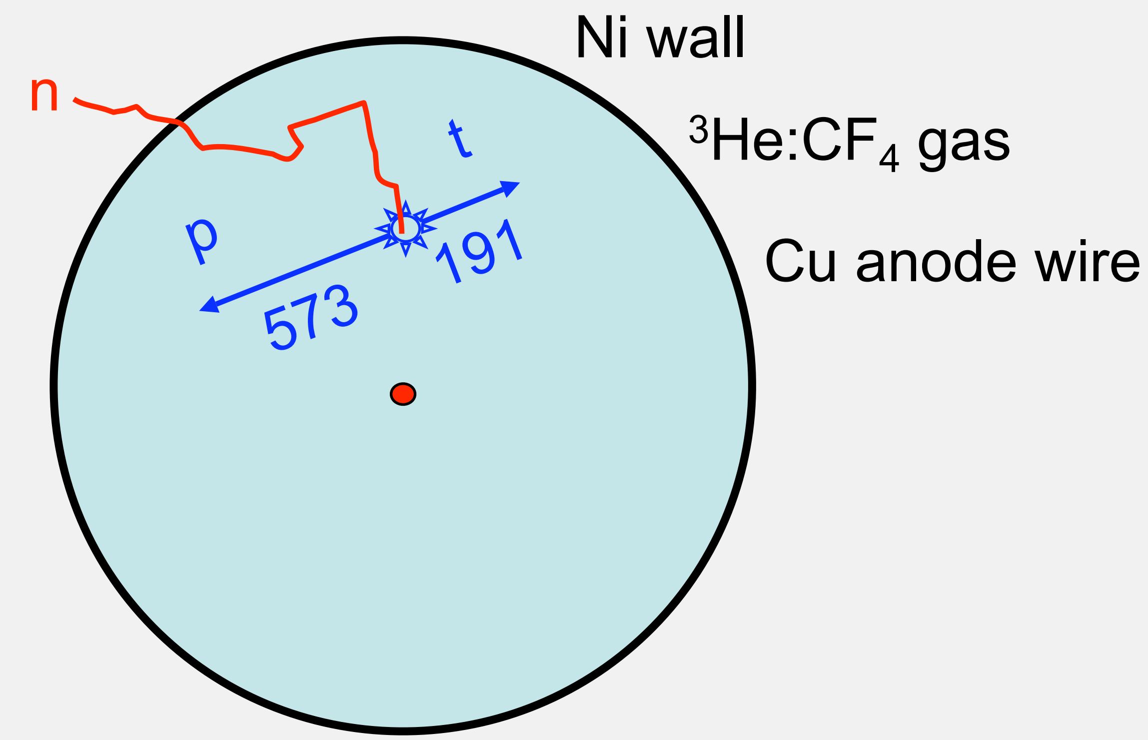

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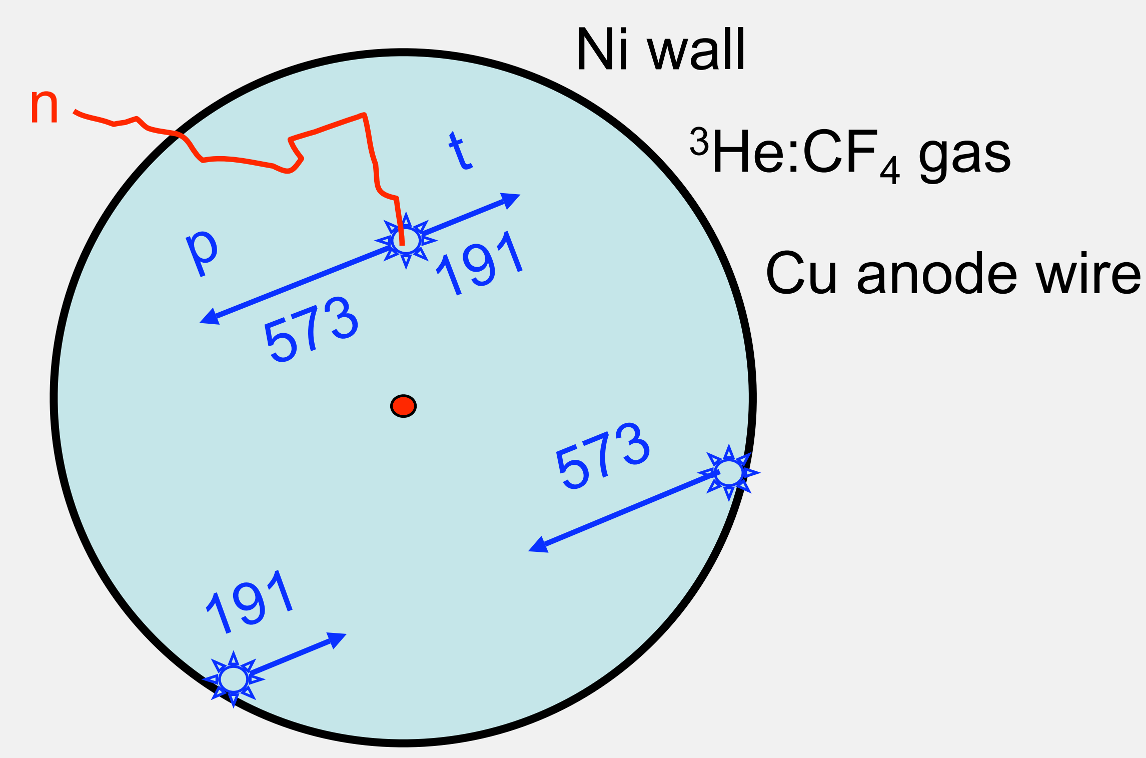

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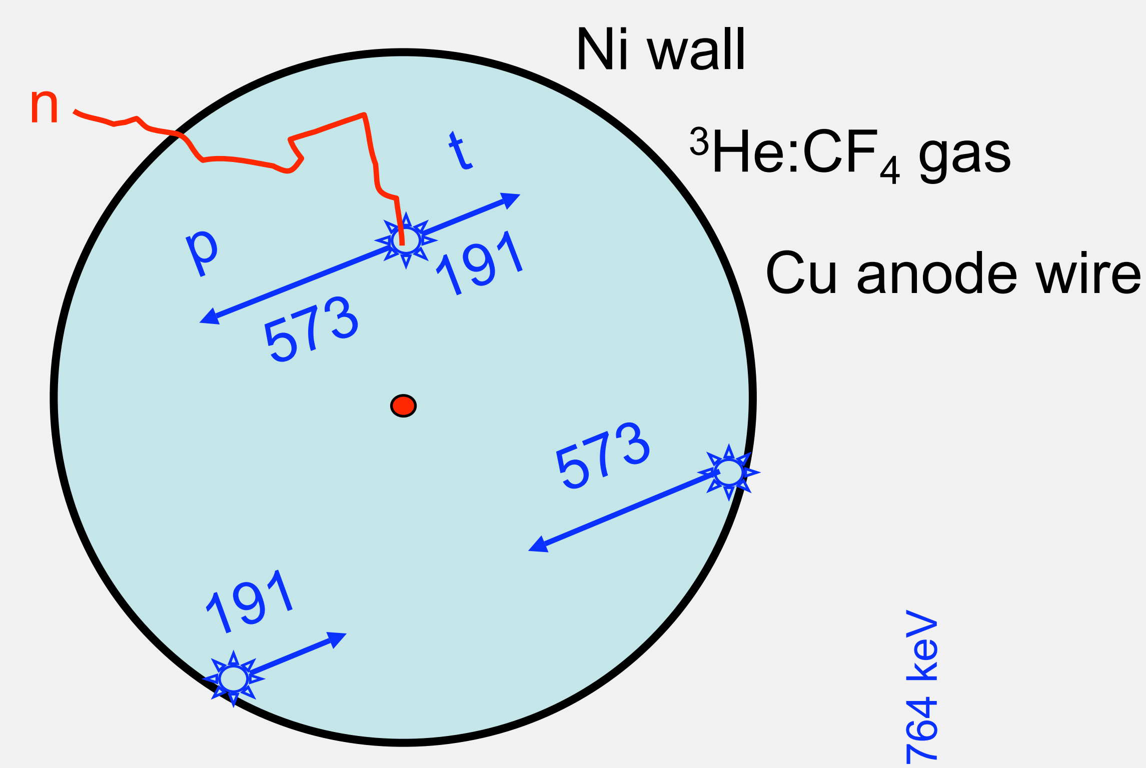
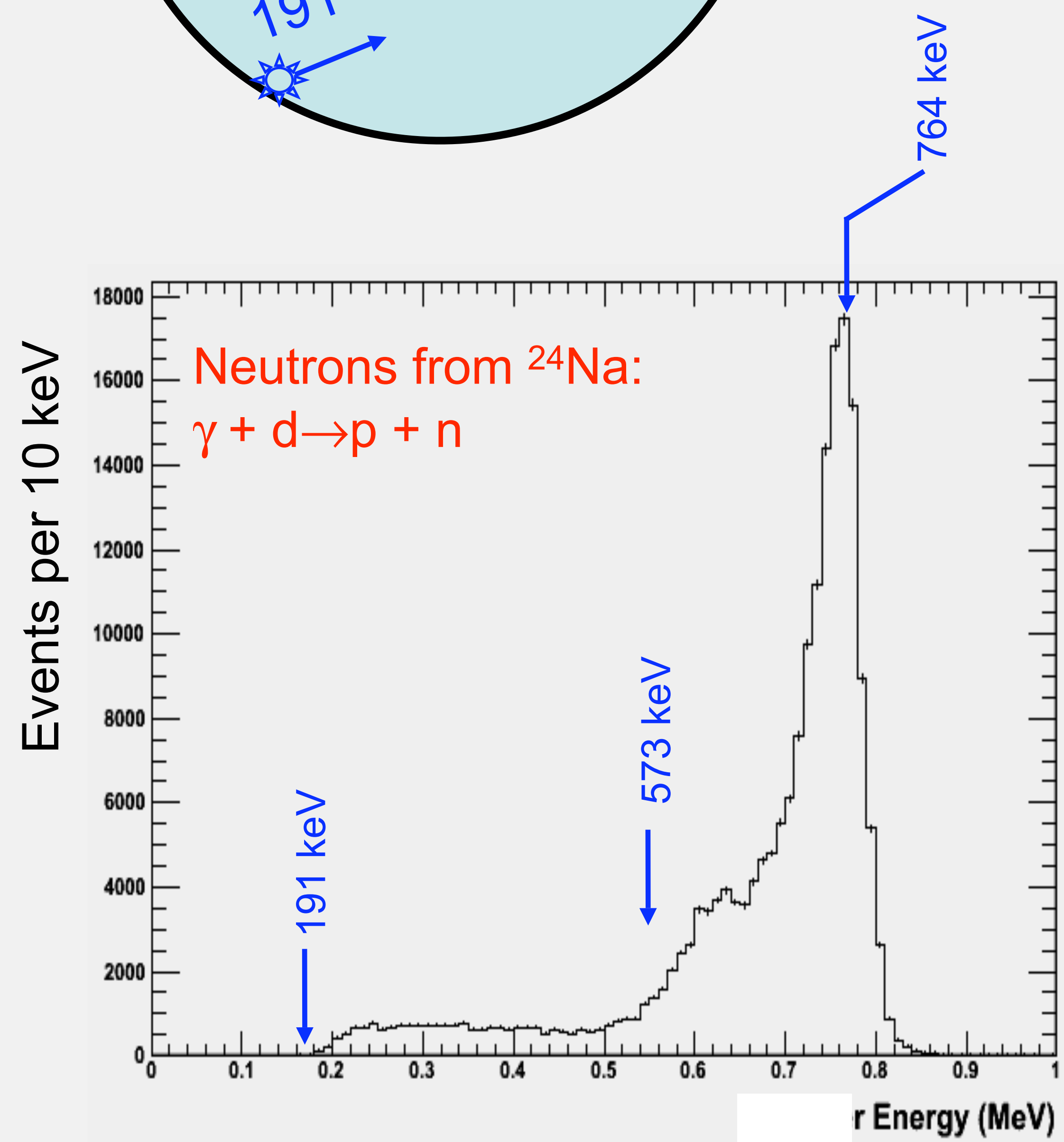
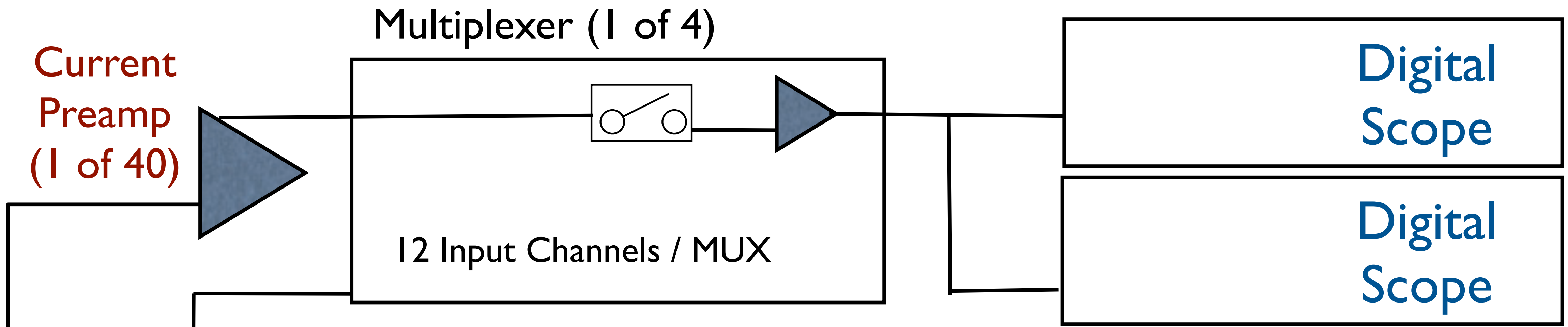
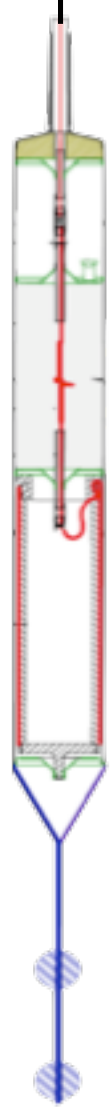
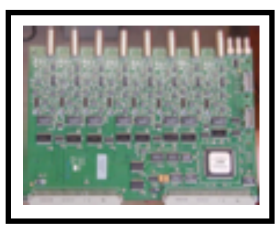


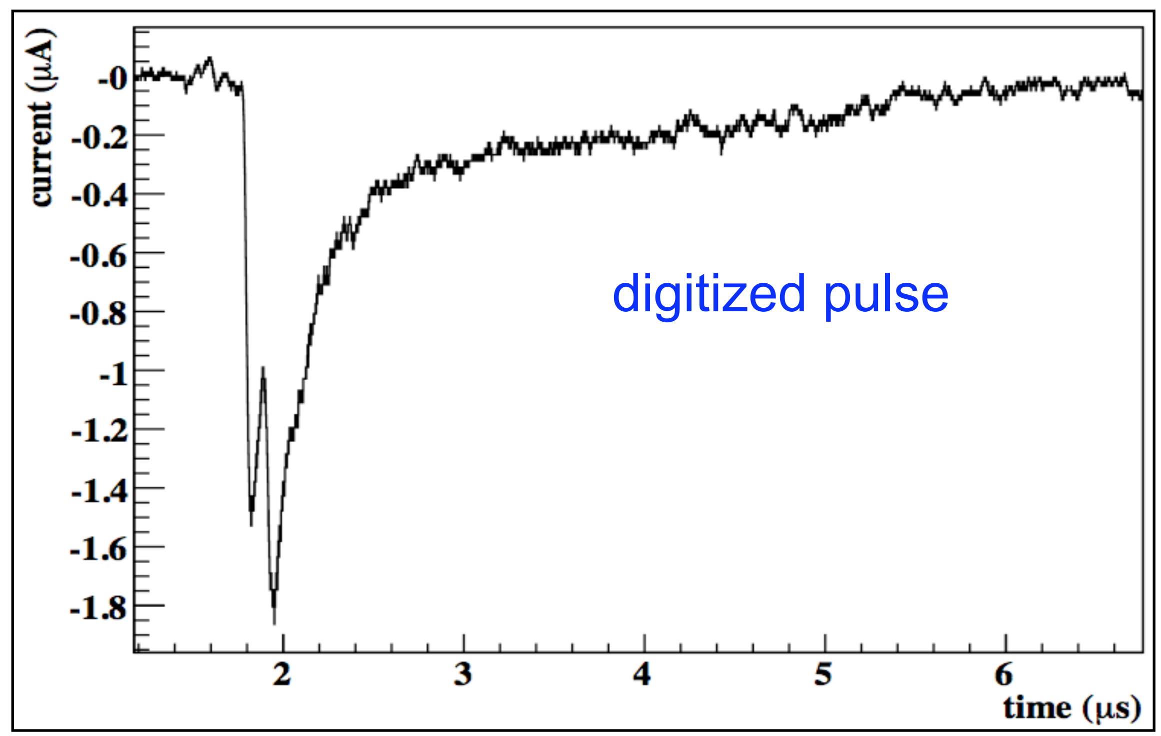


Electronics and Data Acquisition



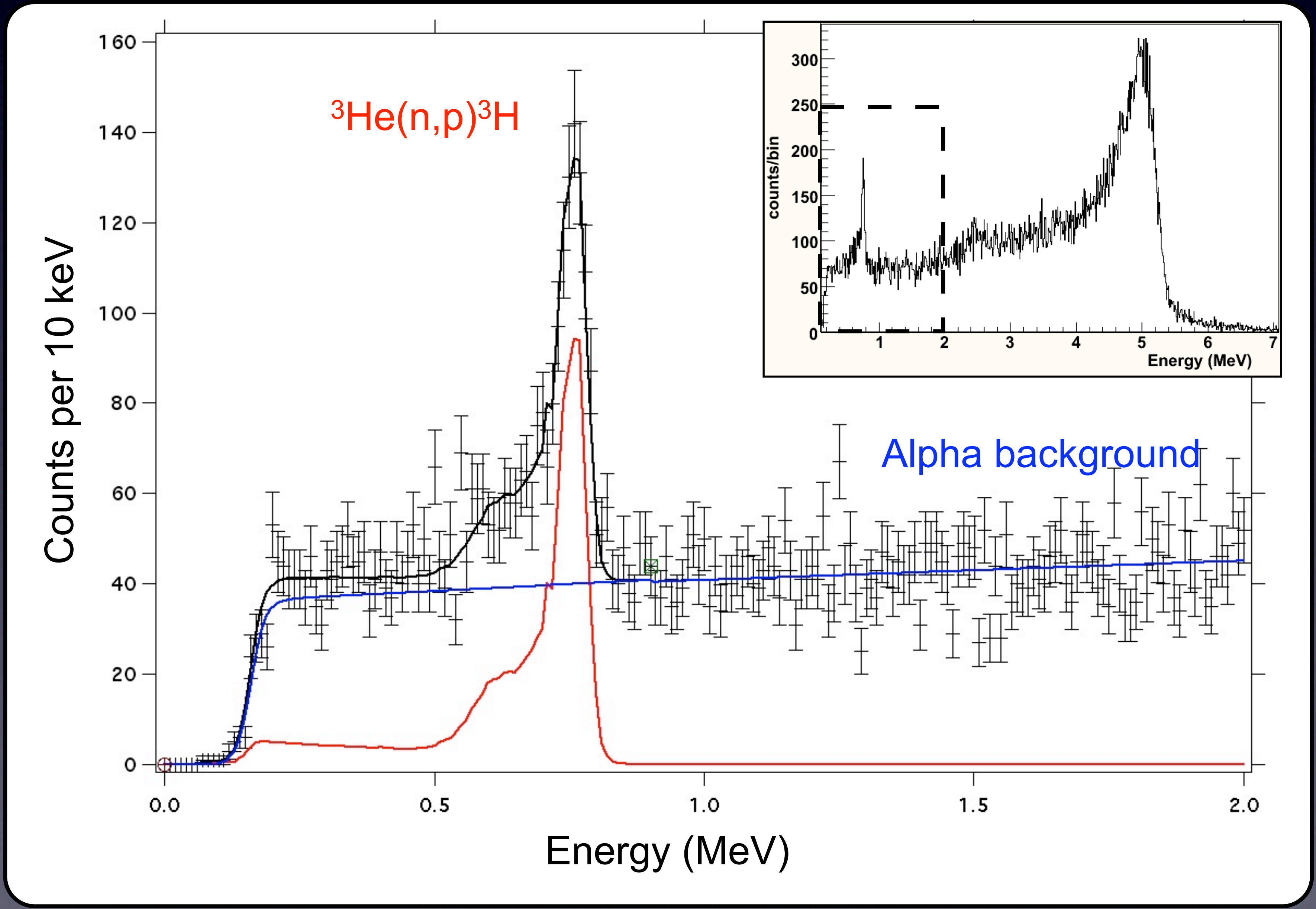






- Digitized pulse from ionization provides detailed information of event (but limited to 2 Hz)
- Current integration provides fast measurement of total charge deposited (negligible deadtime)

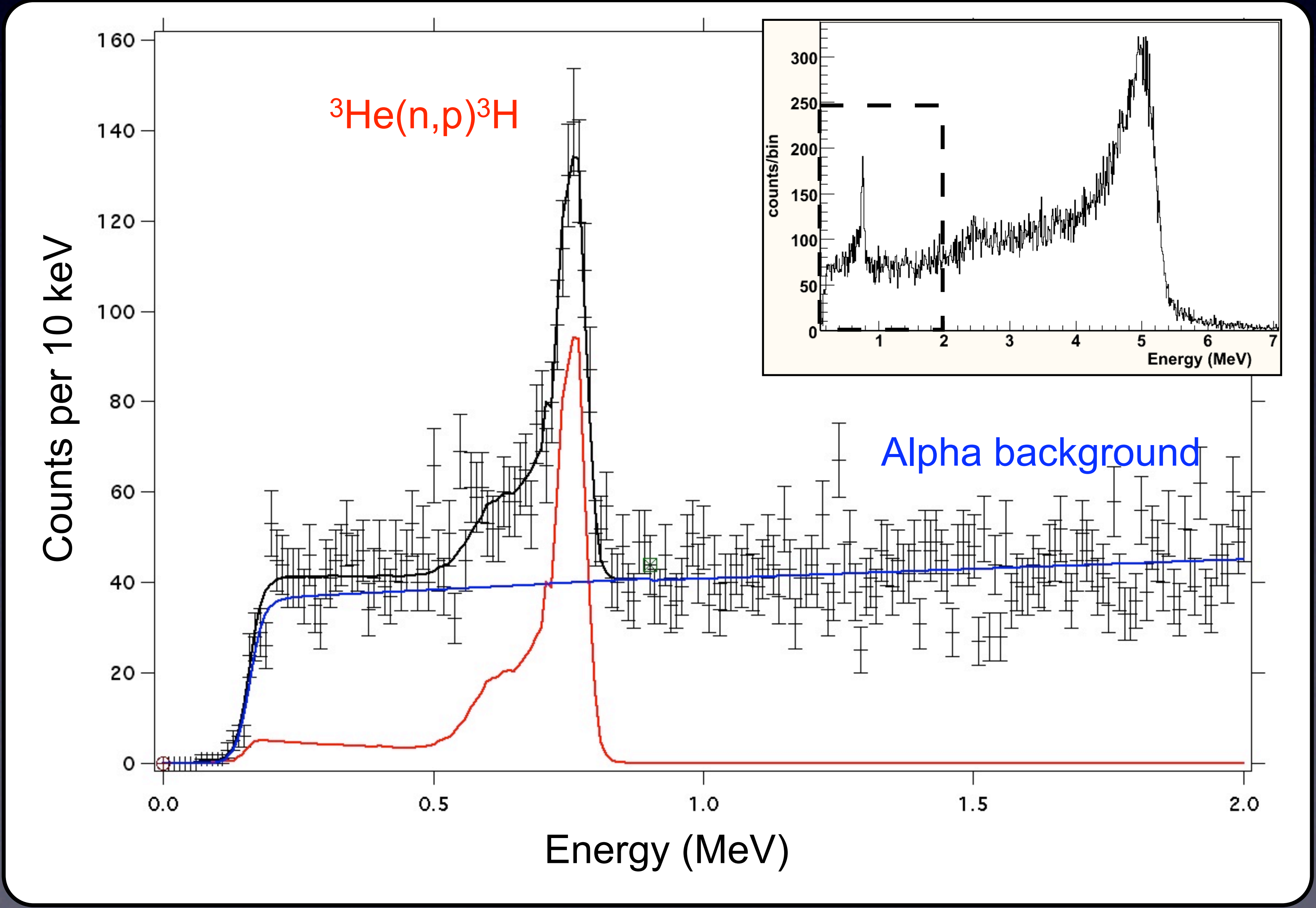
Neutrons & Alphas



Neutrons & Alphas

Neutron Signal:

- Use point and diffuse sources to extract absolute efficiency.
- Compare to MC predictions.



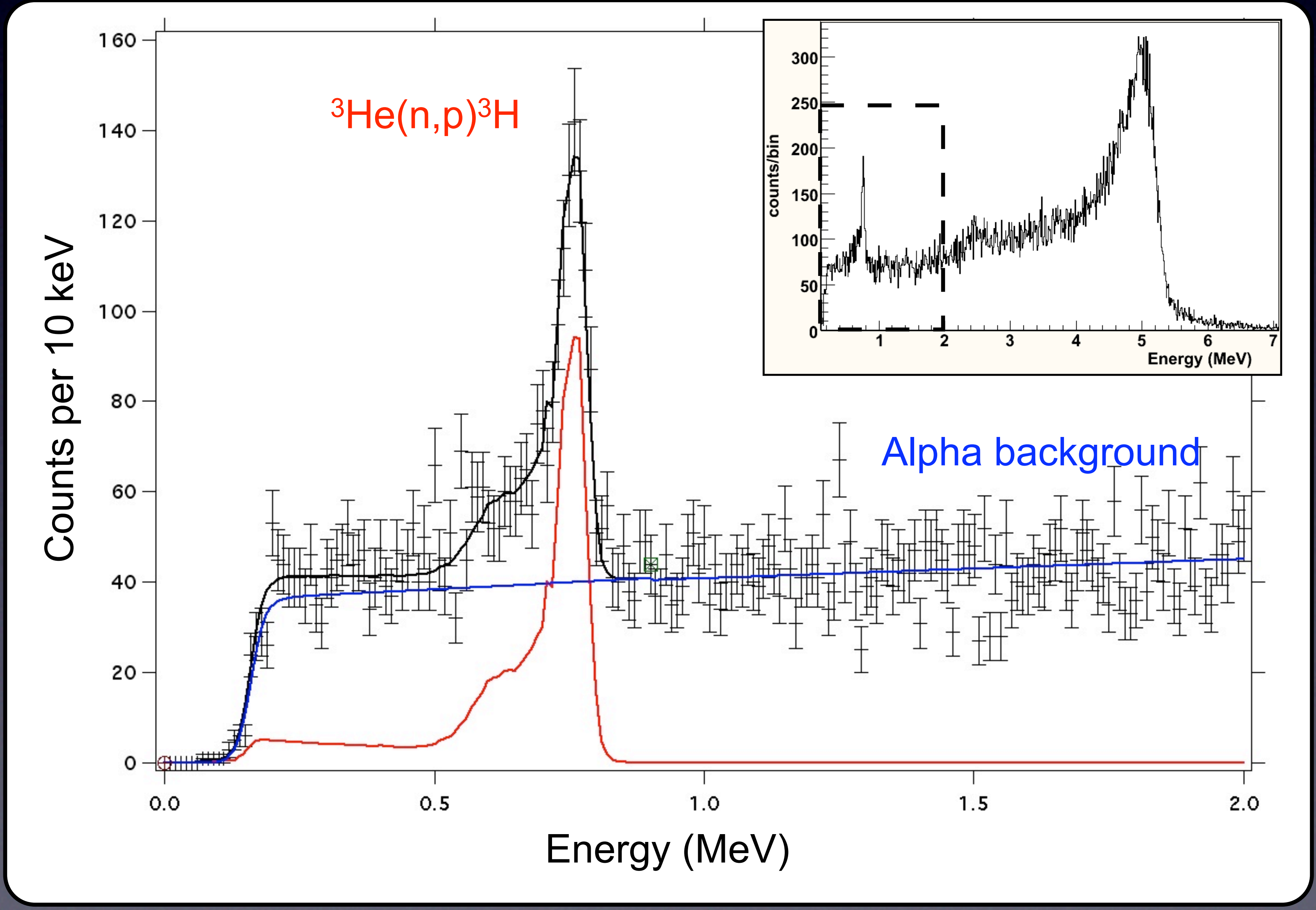
Neutrons & Alphas

Neutron Signal:

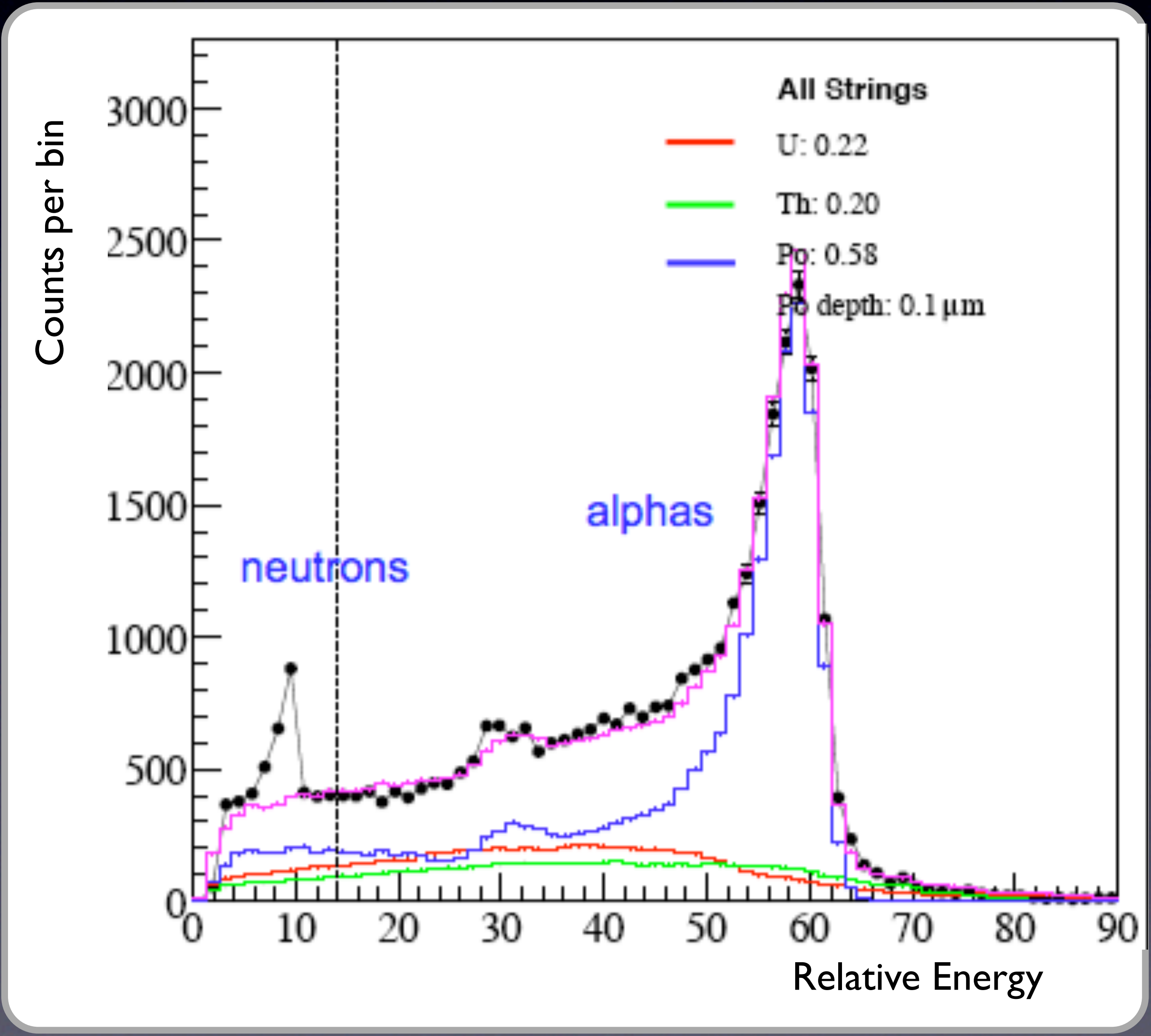
- Use point and diffuse sources to extract absolute efficiency.
- Compare to MC predictions.

Alpha Contamination:

- Alphas from U, Th, and Po chains provide a continuous background that contaminates the neutron energy window.
- Use Monte Carlo, pulse shapes, and ^{4}He counters to help constrain backgrounds.



Monte Carlo Model



Model

- Energy loss and straggling
- Multiple scattering
- Electron-ion pair generation
- Electron drift & diffusion
- Ion mobility
- Electron avalanche
- Space charge
- Electronics model

Fit Parameters

- Po/bulk ratio
- Energy scale
- Energy resolution
- Po depth
- Contribution from sources

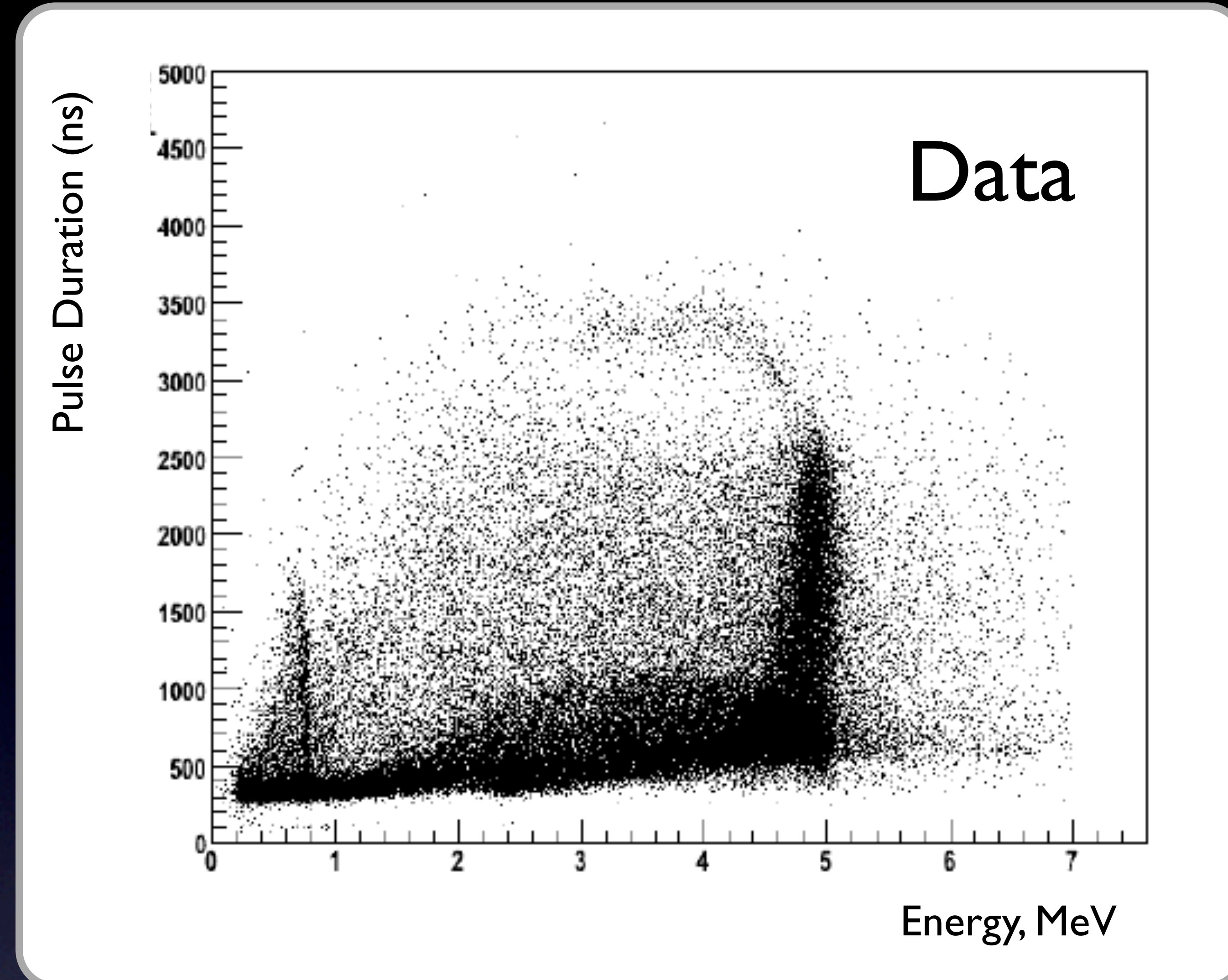
- To help characterize alpha background, a full GARFIELD-based Monte Carlo was developed for NCD proportional counters.
- Comprehensive simulation of many particle-gas interactions.
- Five parameters tuned to calibration data and events above ~ 1 MeV in energy.

Predictions...

- Monte Carlo helped discover and characterize events in the data previously not understood.

- Overall good qualitative and quantitative agreement with calibration data.

Predictions...



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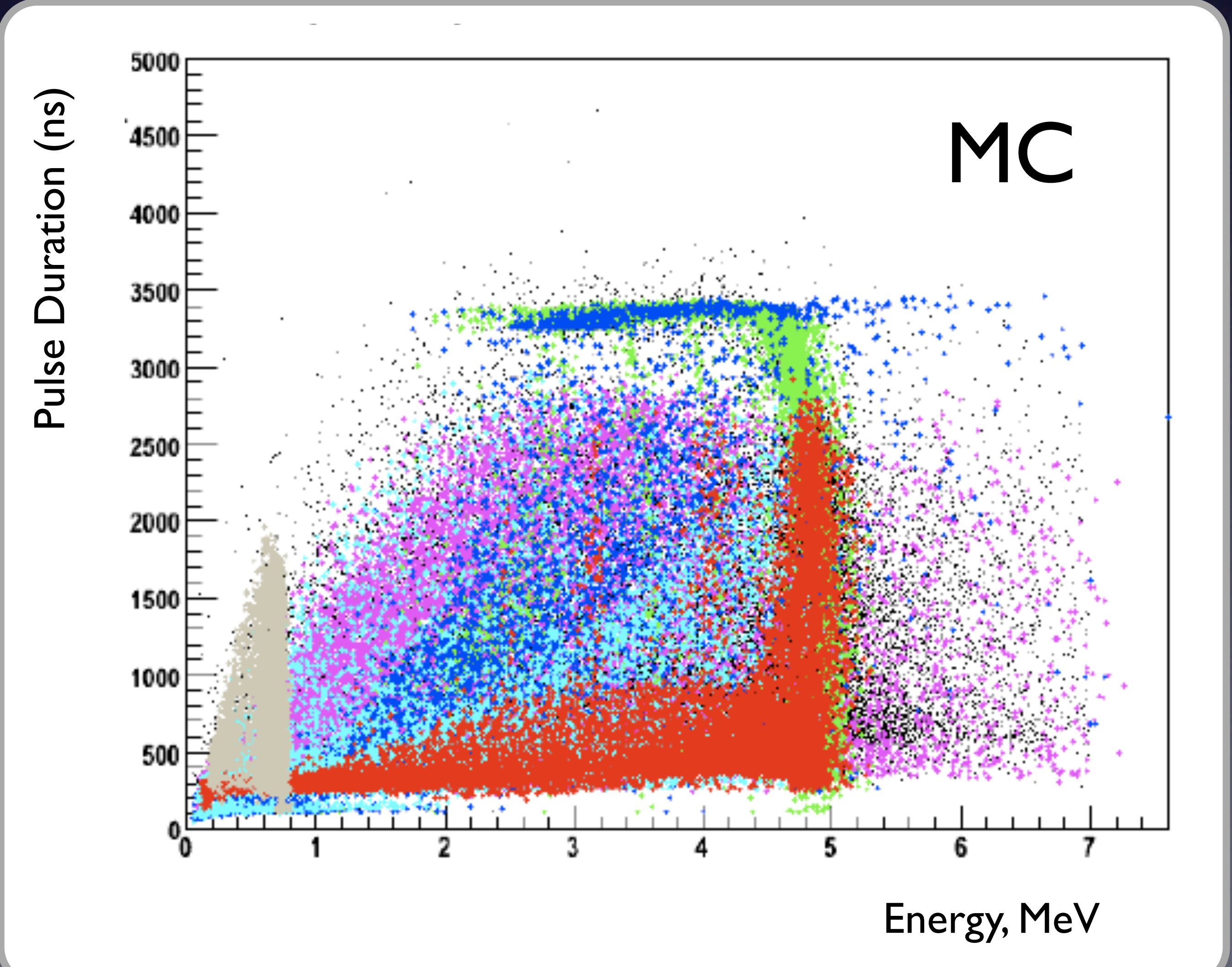
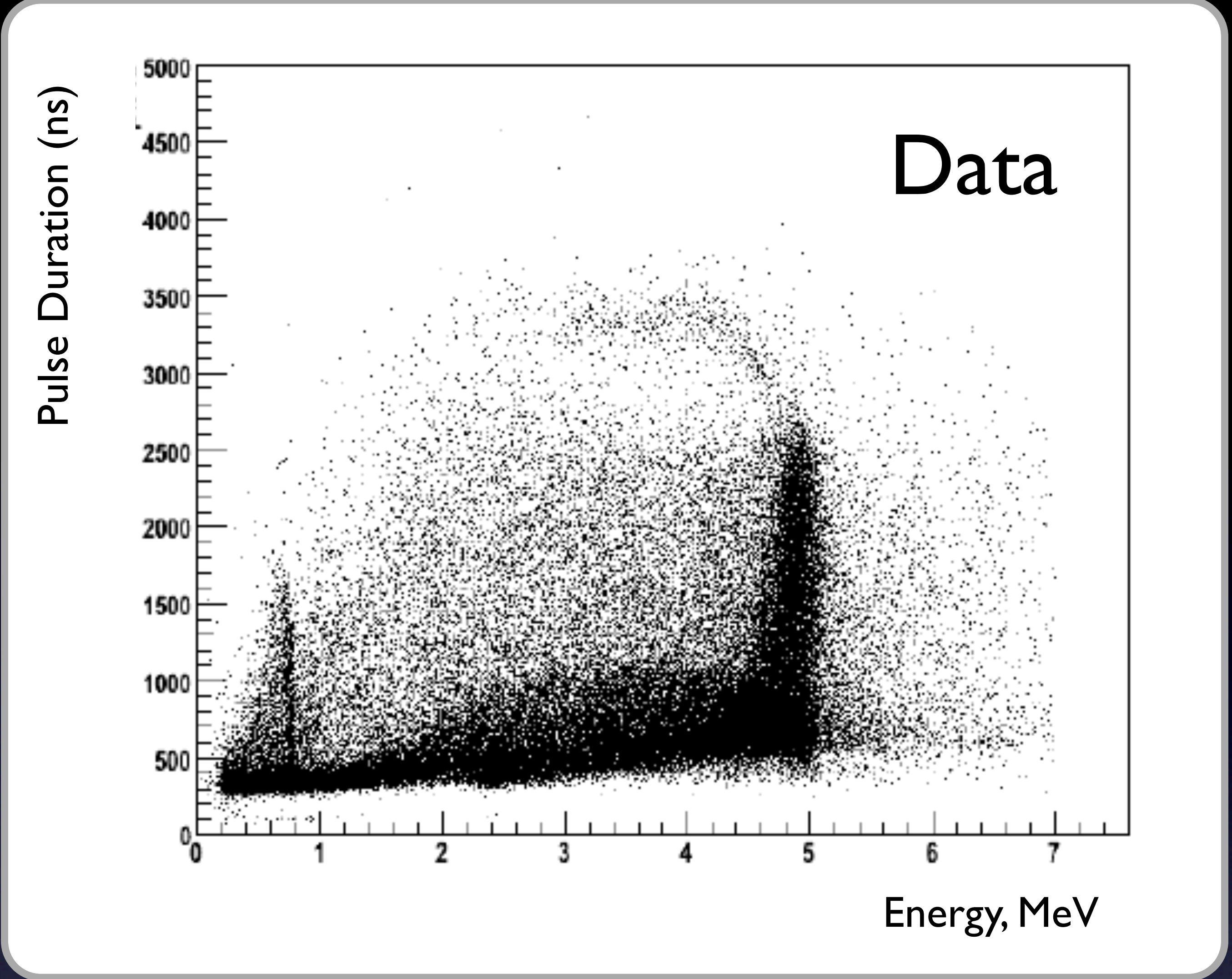
Predictions...

neutron signal
surface polonium decay
bulk U and Th decay
wire polonium decay
wire bulk decay
insulator polonium decay
insulator bulk U and Th decay





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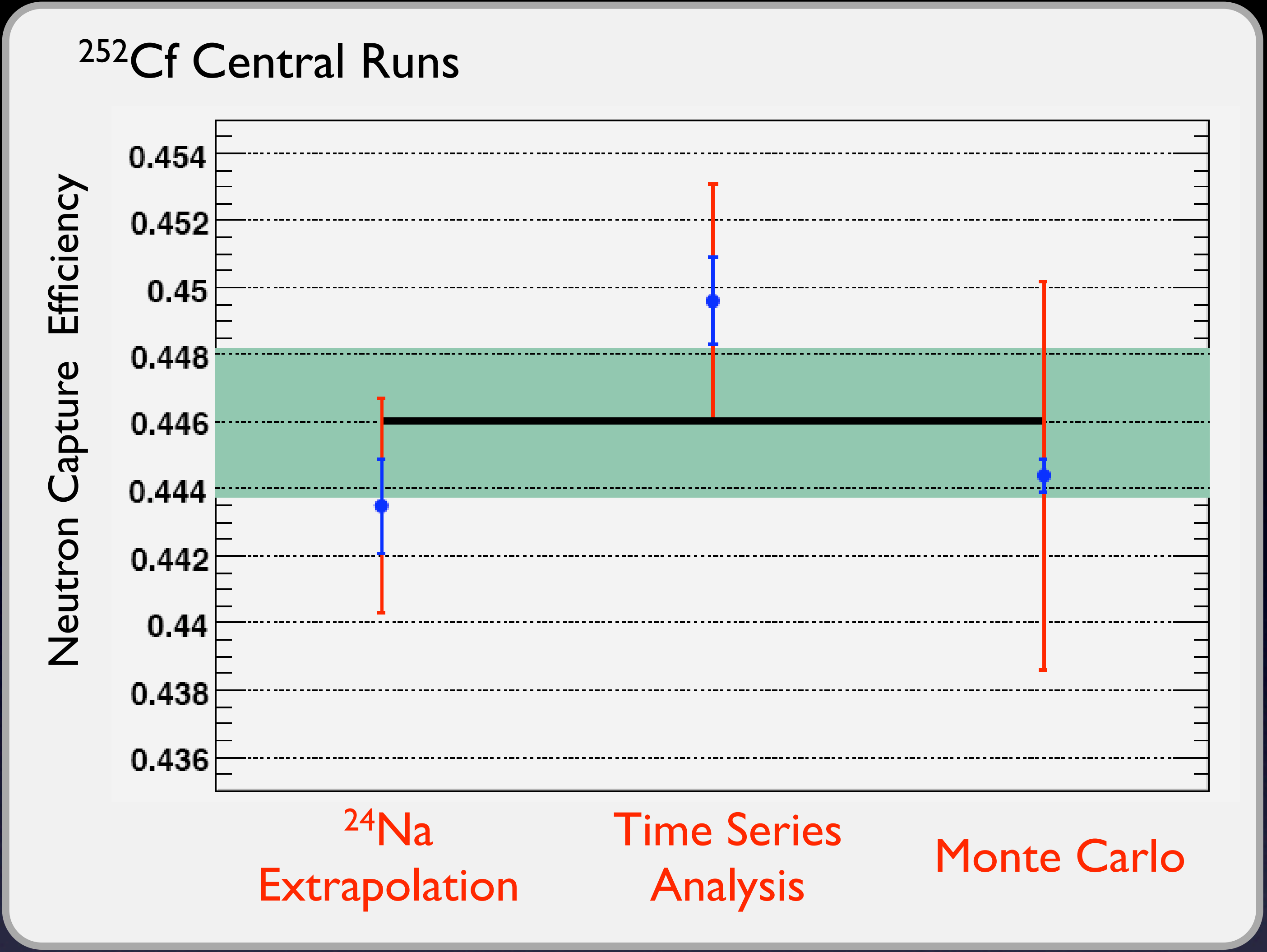
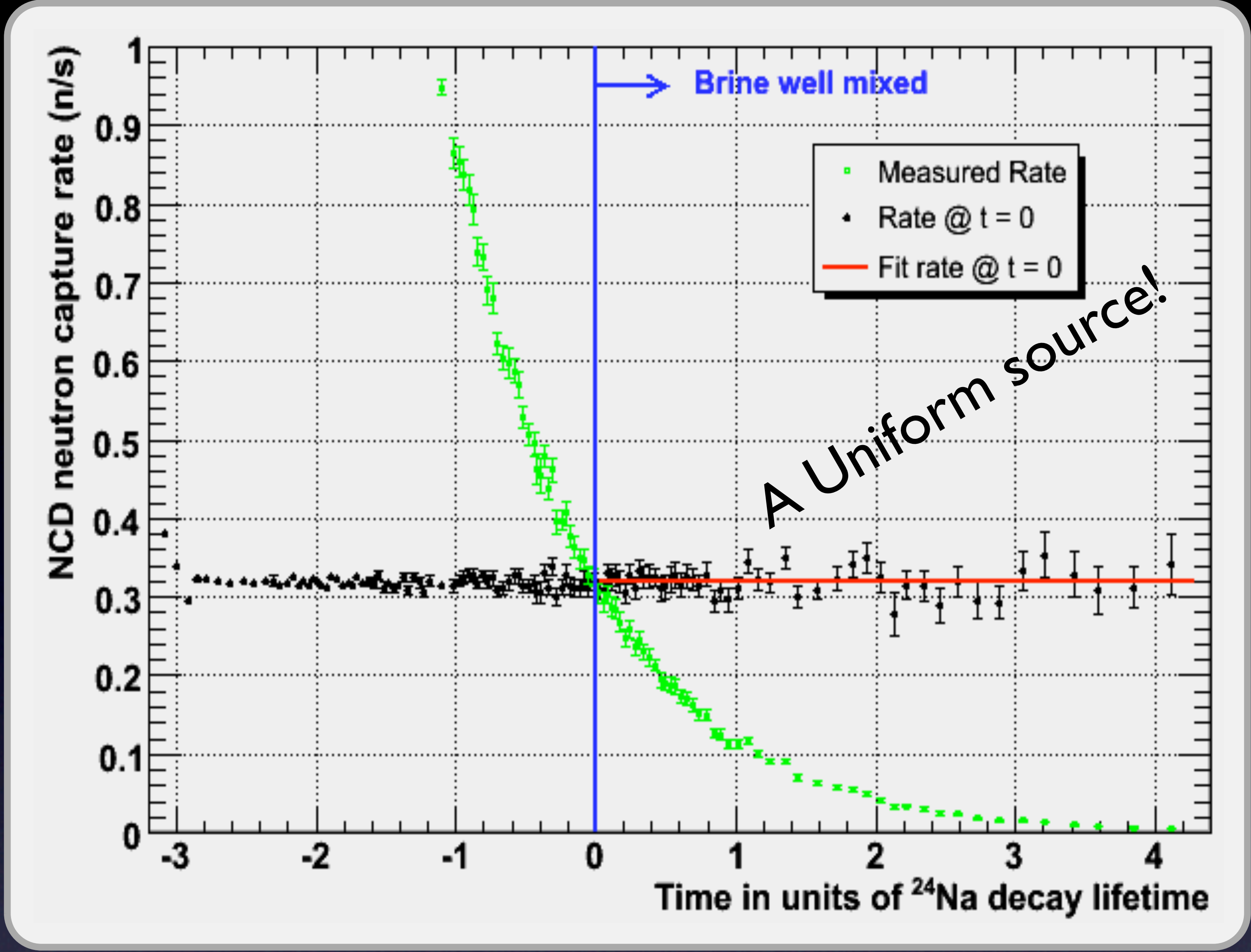
Neutron Calibration

- Neutrons from solar neutrino interactions produce a uniform source distribution in the D_2O.
- Use a variety of techniques to verify neutron efficiency:
  - Monte Carlo predictions (MCNP)
  - Time series analysis of neutron bursts from ^{252}Cf
  - Point sources from AmBe calibration.
  - Injections of ^{24}Na gamma source (see next slide)



Uniform Neutron Source

- Ideal to also use a uniform neutron to determine absolute neutron efficiency.
- Use of two (2) ^{24}Na spike injected via NaCl brine.
- Activated sodium allowed to mix; the 2.75-MeV γ break up deuteron, providing neutrons in D_2O volume.



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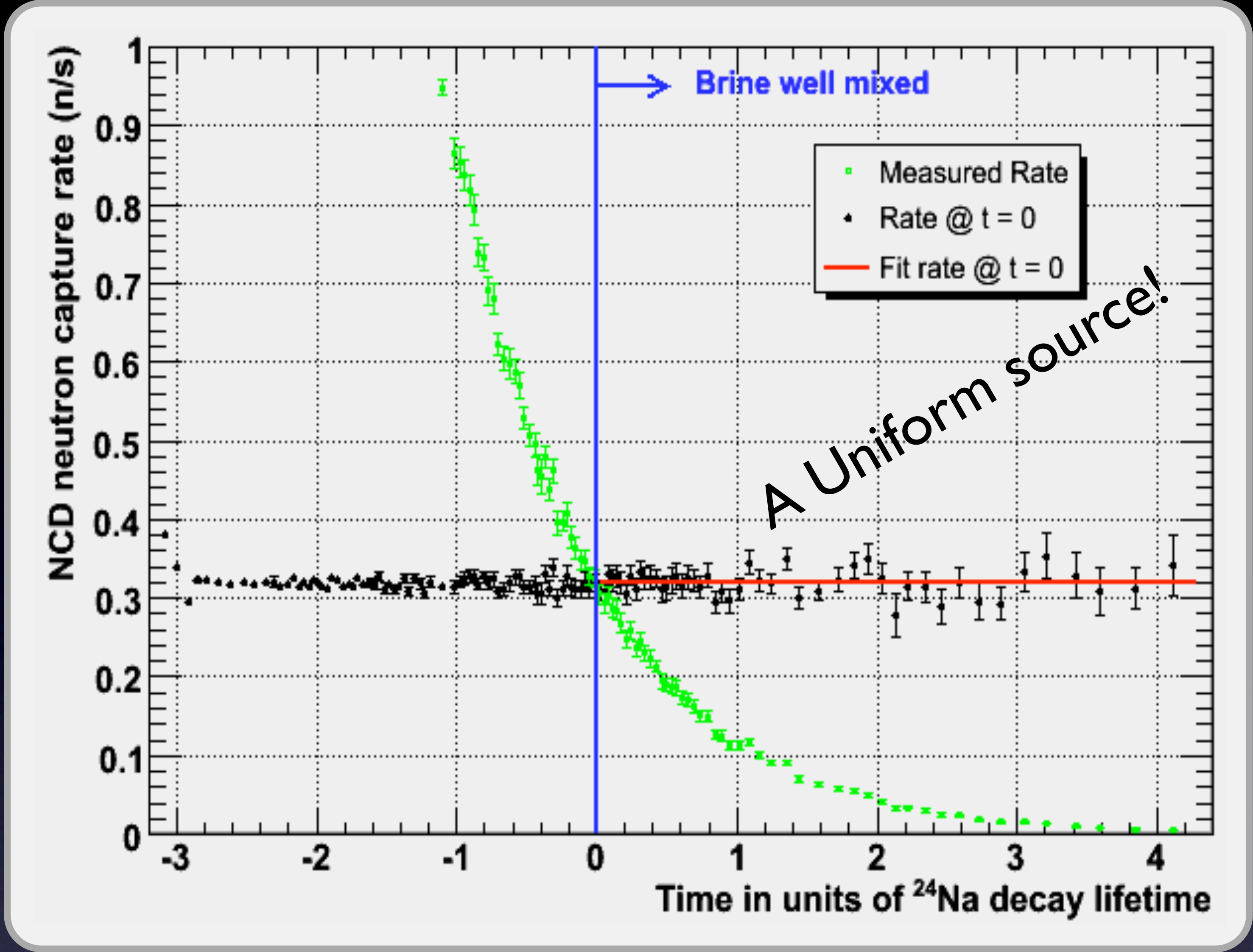

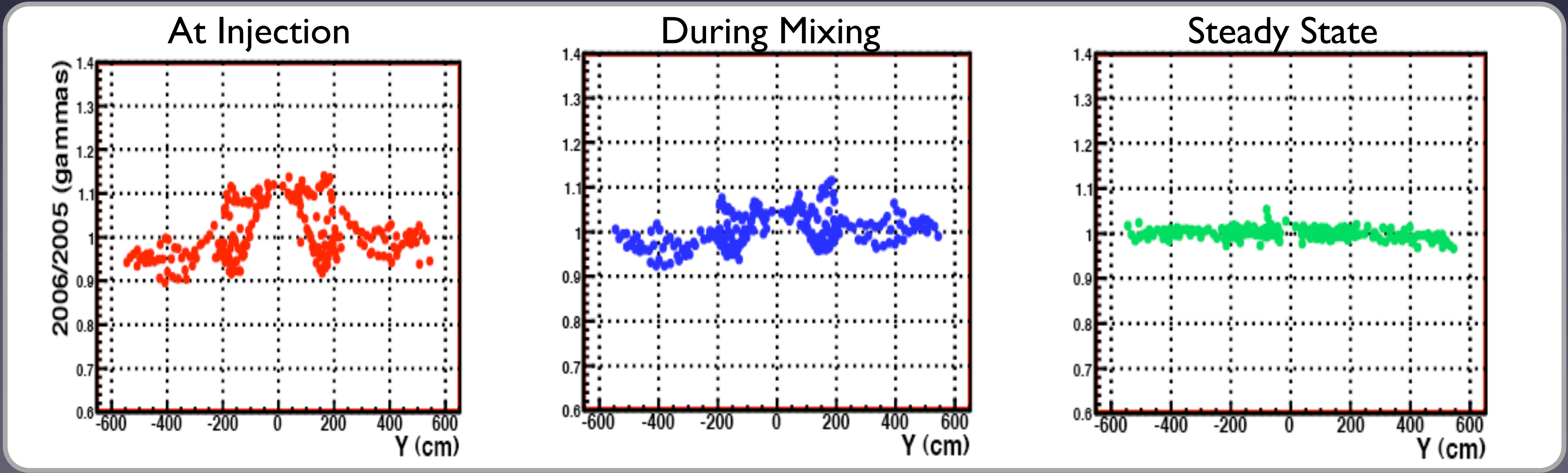

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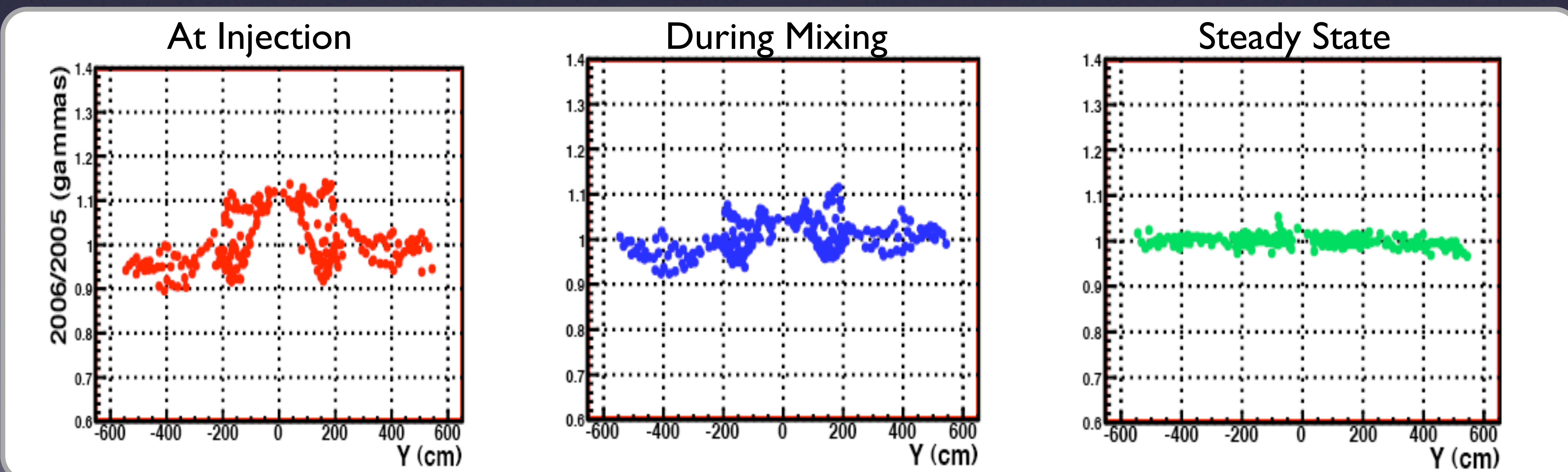
Neutron Detection Efficiency:

21.1 $\pm$ 0.7 % (Data)

21.0 $\pm$ 0.3% (MC)



How to ruin our experiment...

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(1) Take spoonful of dirt (mine dust will do nicely.

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(3) Sit back and enjoy.

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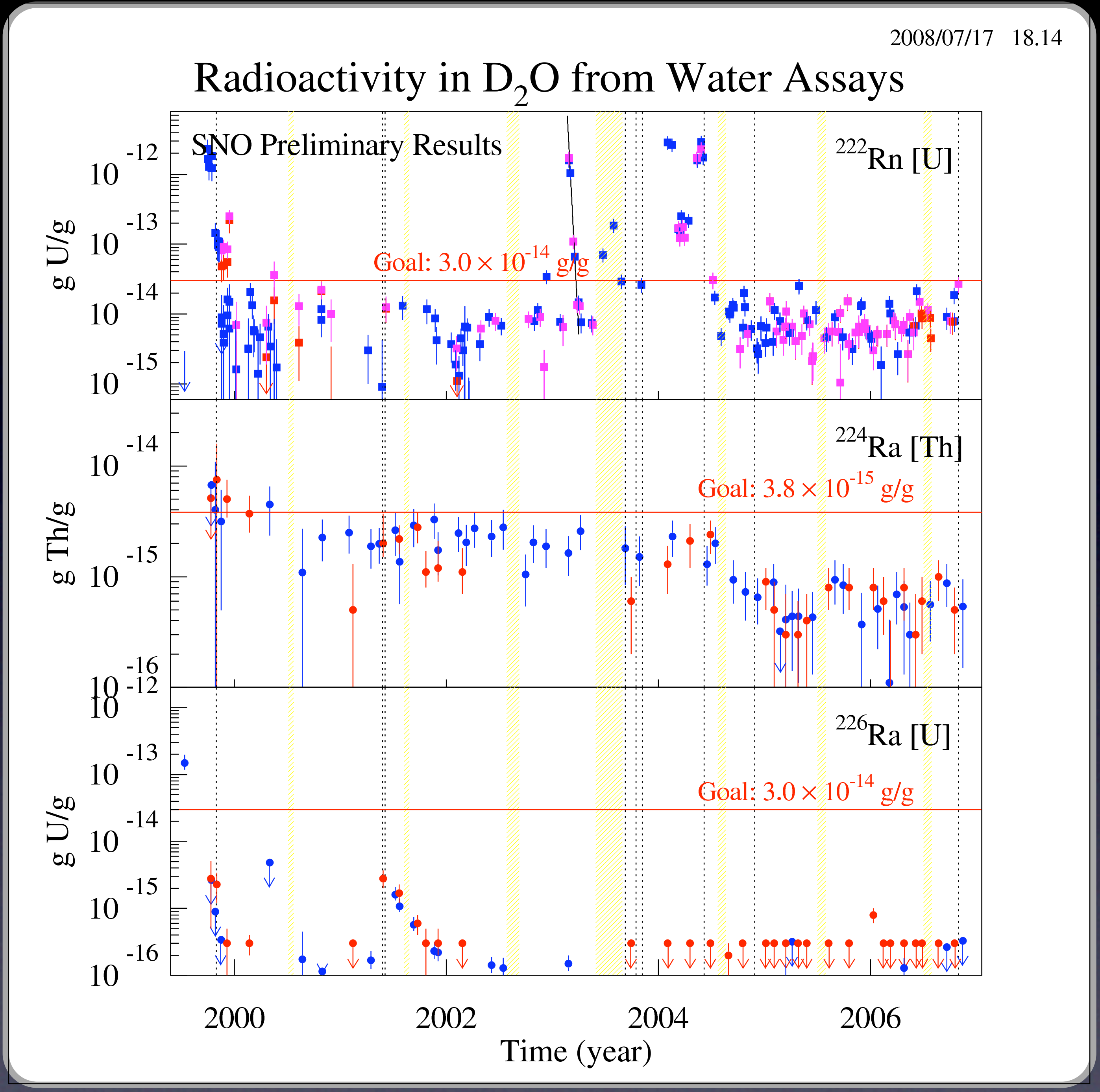
"(Come in under the shadow of this red rock),
And I will show you something different from either
Your shadow at morning striding behind you
Or your shadow at evening rising to meet you;
I will show you fear in a handful of dust."

--T.S. Eliot, The WasteLand

Radioactive Backgrounds

- Uranium and thorium contamination needs to be known, since gamma disintegration can add neutrons to total detected rate.
- Radon levels monitored using both in-situ and ex-situ techniques (techniques consistent with one another).
- U/Th levels considerably lower than previous phases



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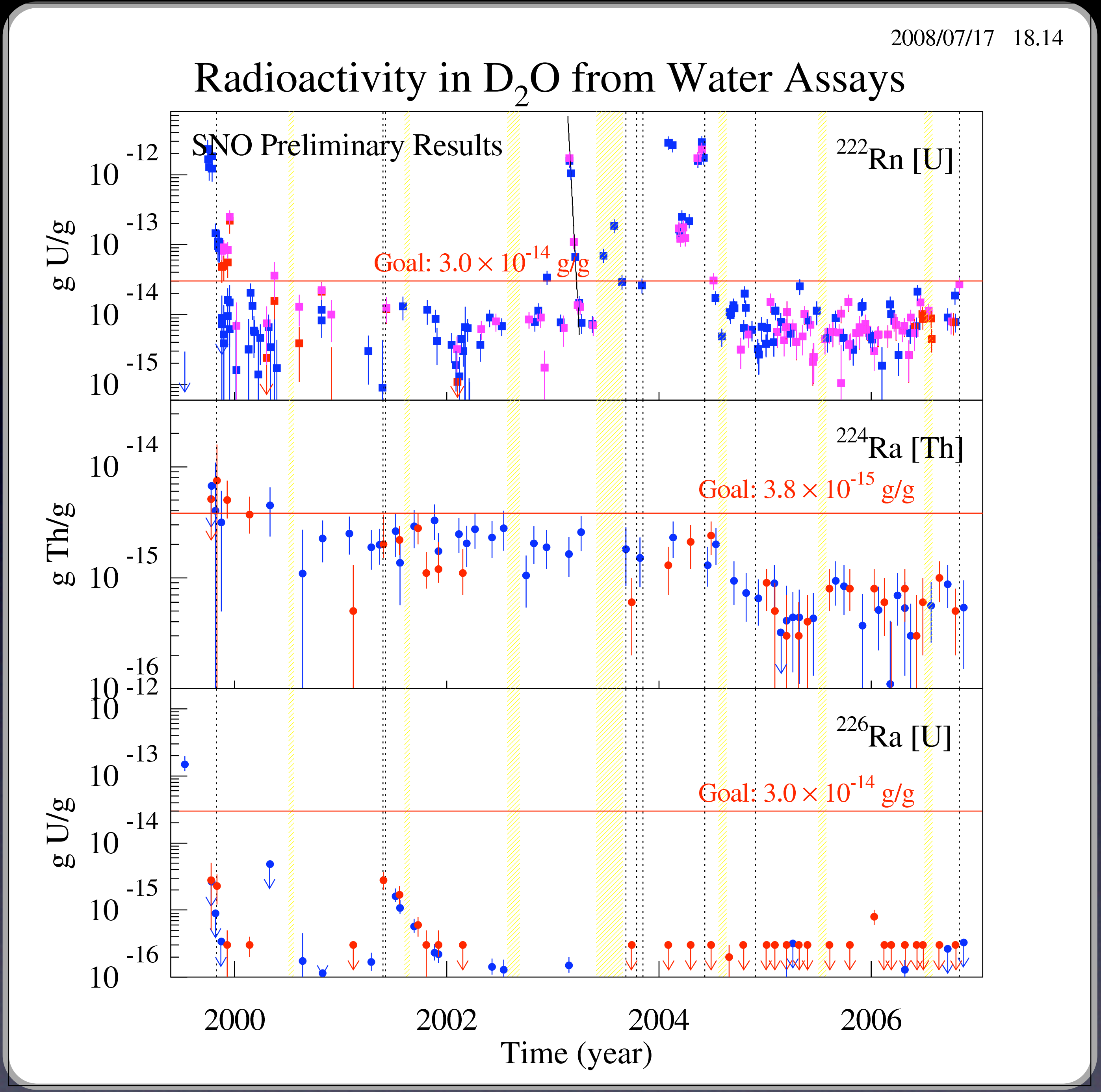
	Ex-Situ	In-Situ	Merged
fgTh/gD₂O	0.88 + 0.27	0.58 + 0.35	0.77 + 0.21
fgU/gD2O	6.63 + 1.22	5.10 + 1.80	6.14 + 1.01



Total Backgrounds

Other backgrounds stem from NCD bulk activity, NCD "hot spots", cables, atmospheric and spallation events and AV radioactivity.

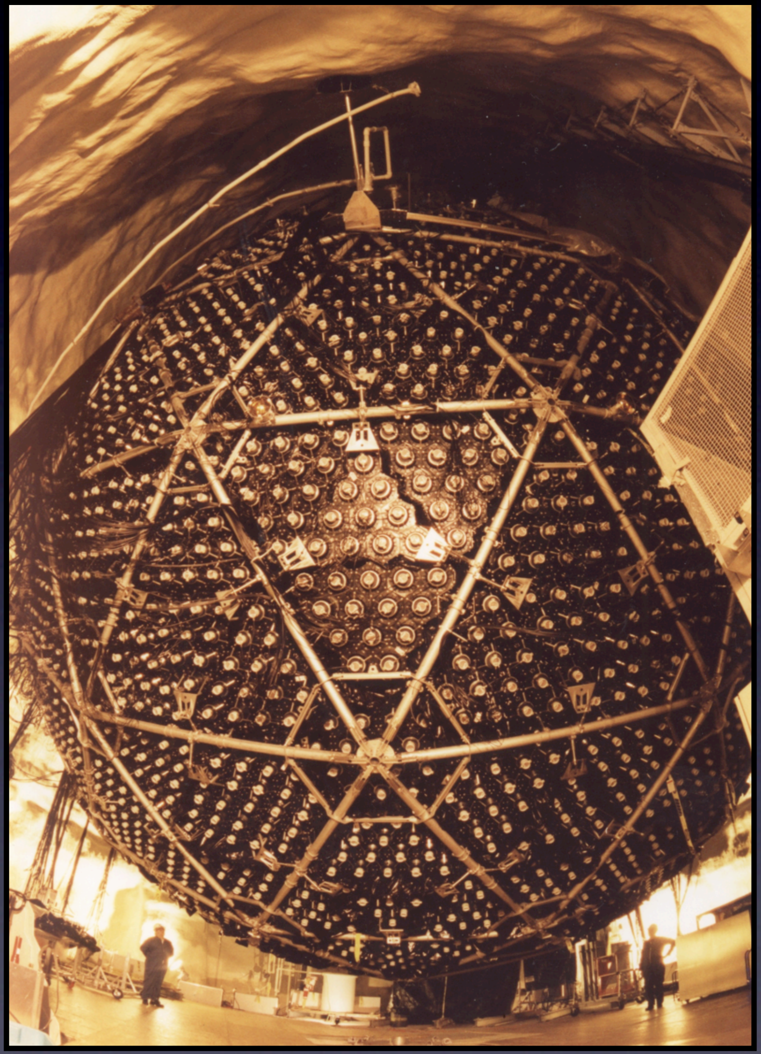
Source	PMT Events (neutrons)	NCD Events (neutrons)
D_2O Radioactivity	7.6 ± 1.2	28.7 ± 4.7
Atmospheric ν, ^{16}N	24.7 ± 4.6	13.6 ± 2.7
Other backgrounds	0.7 ± 0.1	2.3 ± 0.3
NCD Bulk PD, $^{17,18}O(\alpha,n)$	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
NCD hotspots	17.7 ± 1.8	64.4 ± 6.4
NCD cables	1.1 ± 1.0	8.0 ± 5.2
External-source neutrons	20.6 ± 10.4	40.9 ± 20.6
TOTAL	77^{+12}_{-10}	185^{+25}_{-22}

Background/Signal

Error:

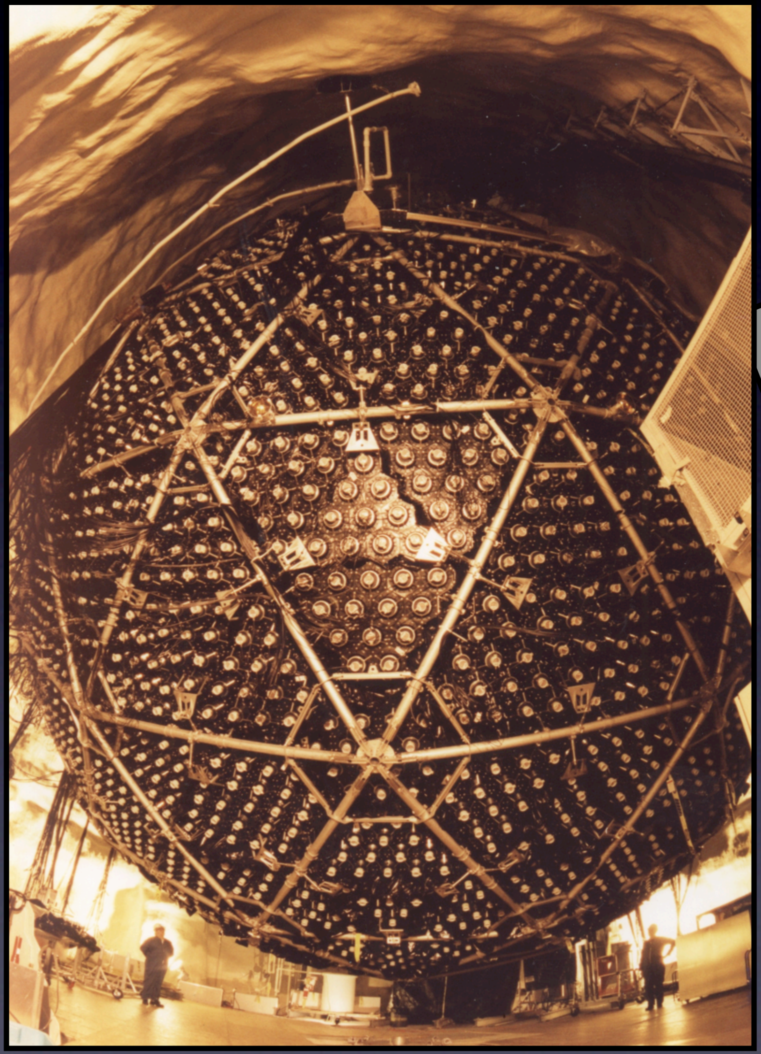
< 2.5%

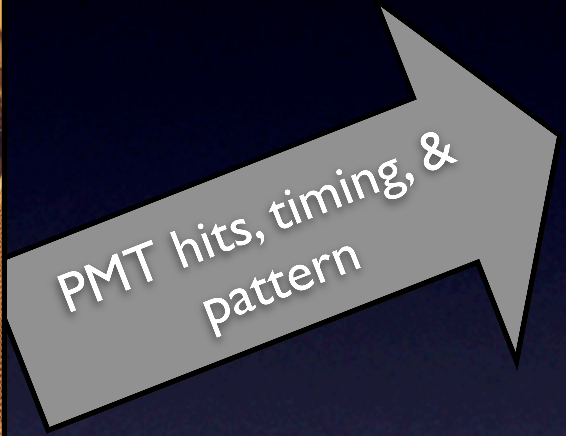
PMT
Signatures



On the PMT side, reconstruction of electrons needed to extract charged current flux.

PMT Signatures





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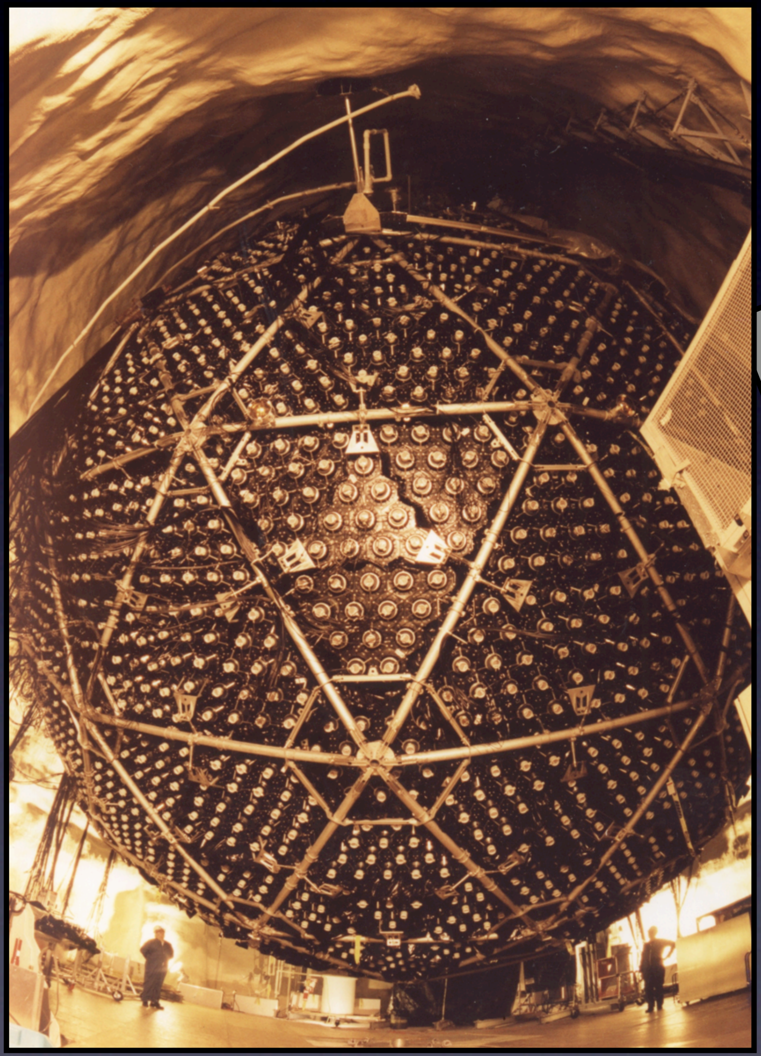
PMT Signatures

Radius:

Flat for electron candidates, shaped for neutrons.



PMT hits, timing, & pattern

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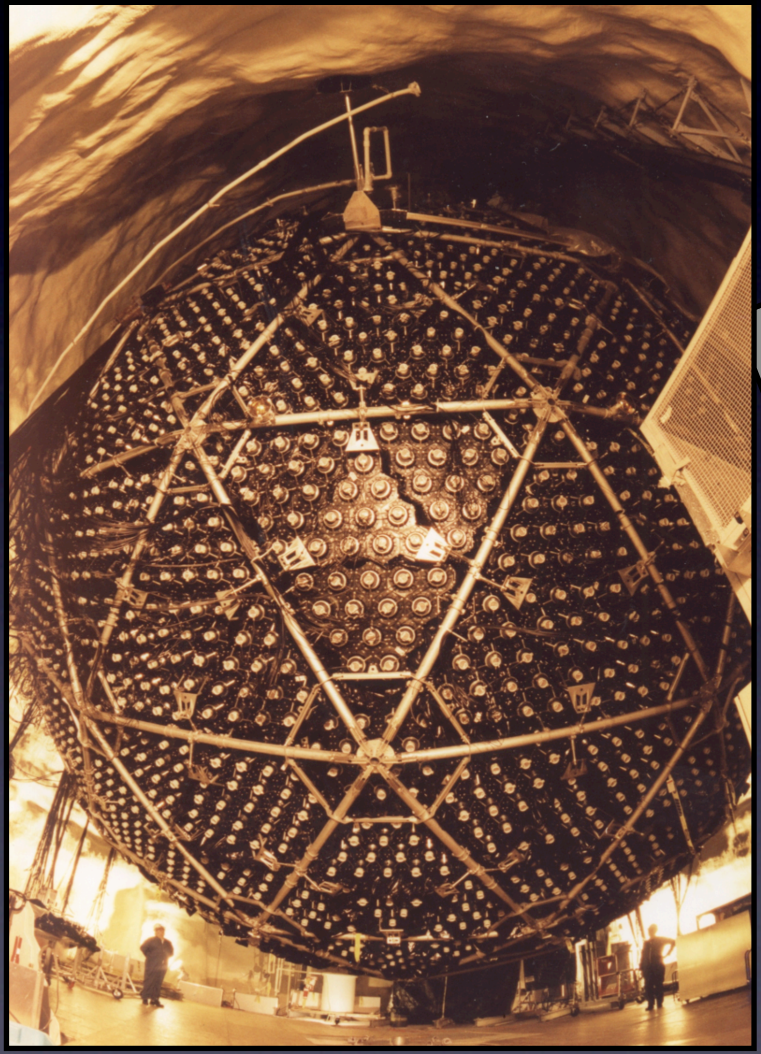
PMT Signatures



PMT hits, timing, & pattern

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Energy:

Dominated by ^{8}B spectrum; some $^{2}H(n,\gamma)^{3}H$ capture

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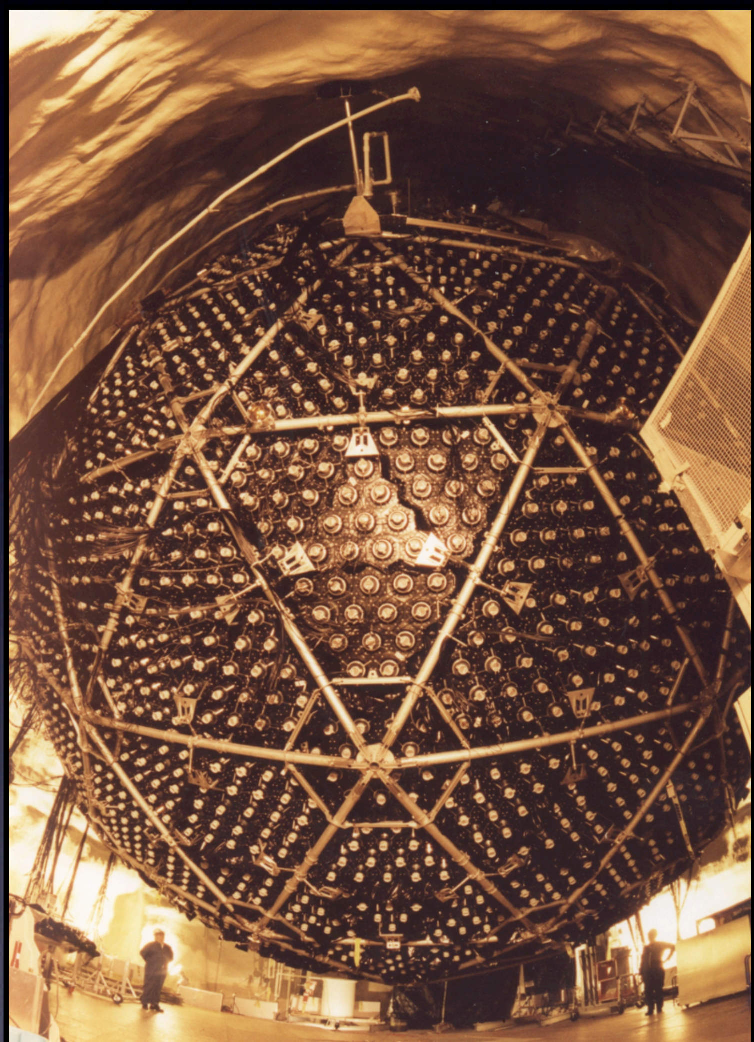

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Angle with respect to the Sun:

Highly correlated with ν_e-e scattering events

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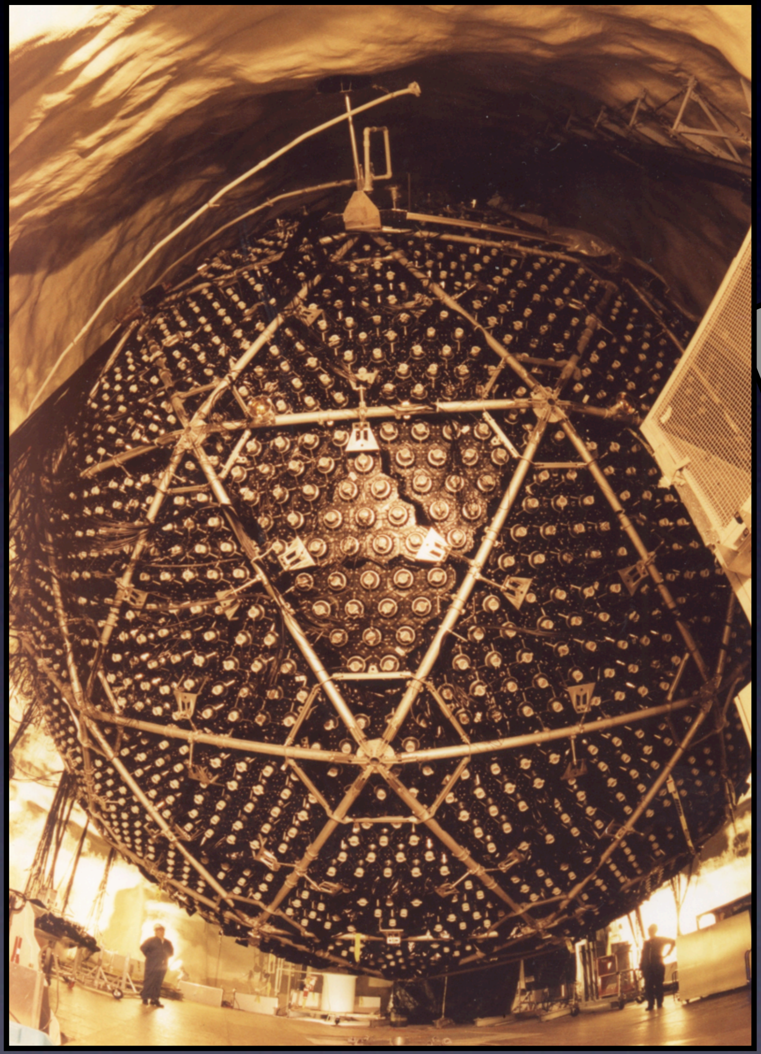

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Angle with respect to the Sun:

Highly correlated with ν_e-e scattering events

also use...

β_{14}:

Helps separate ^{214}Bi and ^{208}Tl events.

On the PMT side, reconstruction of electrons needed to extract charged current flux.

Systematic Errors

The systematics for charged and neutral current reactions now highly decoupled (from ~0.5 to ~0.02).

Source	Neutral Current	Charged Current	Elastic Scattering
PMT Energy Scale	± 0.6%	± 2.7%	± 3.6%
PMT Energy Resolution	± 0.1%	± 0.1%	± 0.3%
PMT Radial Scaling	± 0.1%	± 2.7%	± 2.7%
PMT Angular Resolution	± 0.0%	± 0.2%	± 2.2%
PMT Radial Energy Dep.	± 0.0%	± 0.9%	± 0.9%
Background Neutrons	± 2.3%	± 0.6%	± 0.7%
Neutron Capture	± 3.3%	± 0.4%	± 0.5%
Cherenkov/AV Events	± 0.0%	± 0.3%	± 0.3%
NCD Instrumentals	± 1.6%	± 0.2%	± 0.2%
NCD Energy Scale	± 0.5%	± 0.1%	± 0.1%
NCD Energy Resolution	± 2.7%	± 0.3%	± 0.3%
NCD Alpha Systematics	± 2.7%	± 0.3%	± 0.4%
PMT Data Cleaning	± 0.0%	± 0.3%	± 0.3%
Total Uncertainty	± 6.5%	± 4.0%	± 4.9%

Box Opening...

Three blindness measures to minimize bias on NC and CC signals:

(1) Fraction of data closed

(2) Include hidden fraction of neutrons created from muon interactions.

(3) Omit a unknown fraction of candidate events.

Box opened after detailed internal reviews completed.

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Box opened after detailed internal reviews completed.

Box opened May 2, 2008

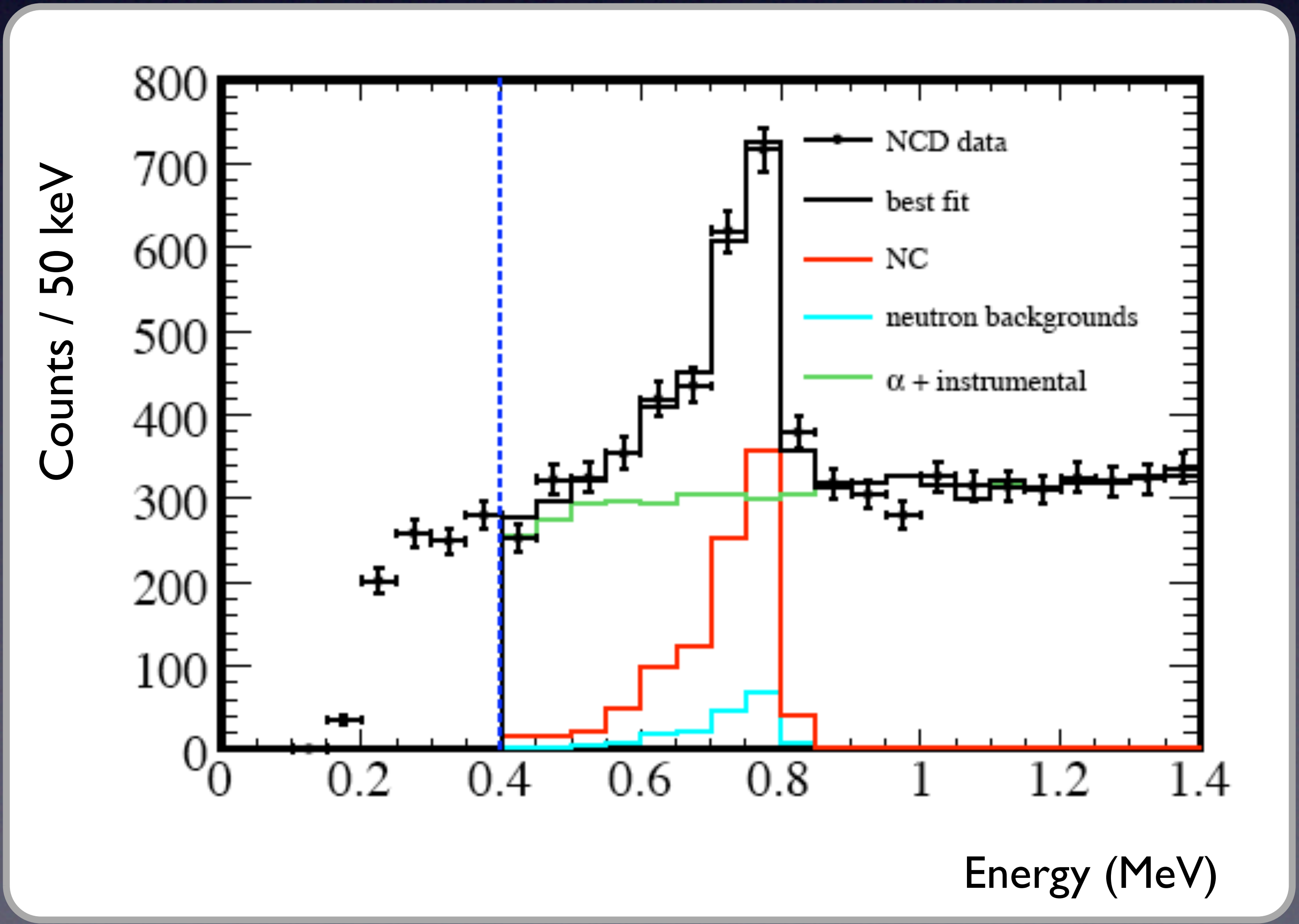
Results presented are as found, except...

1. Difference between uncertainties from the three signal extraction codes. "Pilot errors" corrected. No change in central values and uncertainties agree.

2. An incorrect algorithm in fitting the peak value of the ES posterior distributions replaced.

Signal Neutrons from NCDs

- Having characterized both neutrons and alphas, we can now extract the number of signal neutrons and background alphas.
- Combine with PMT data and extract CC versus NC flux.



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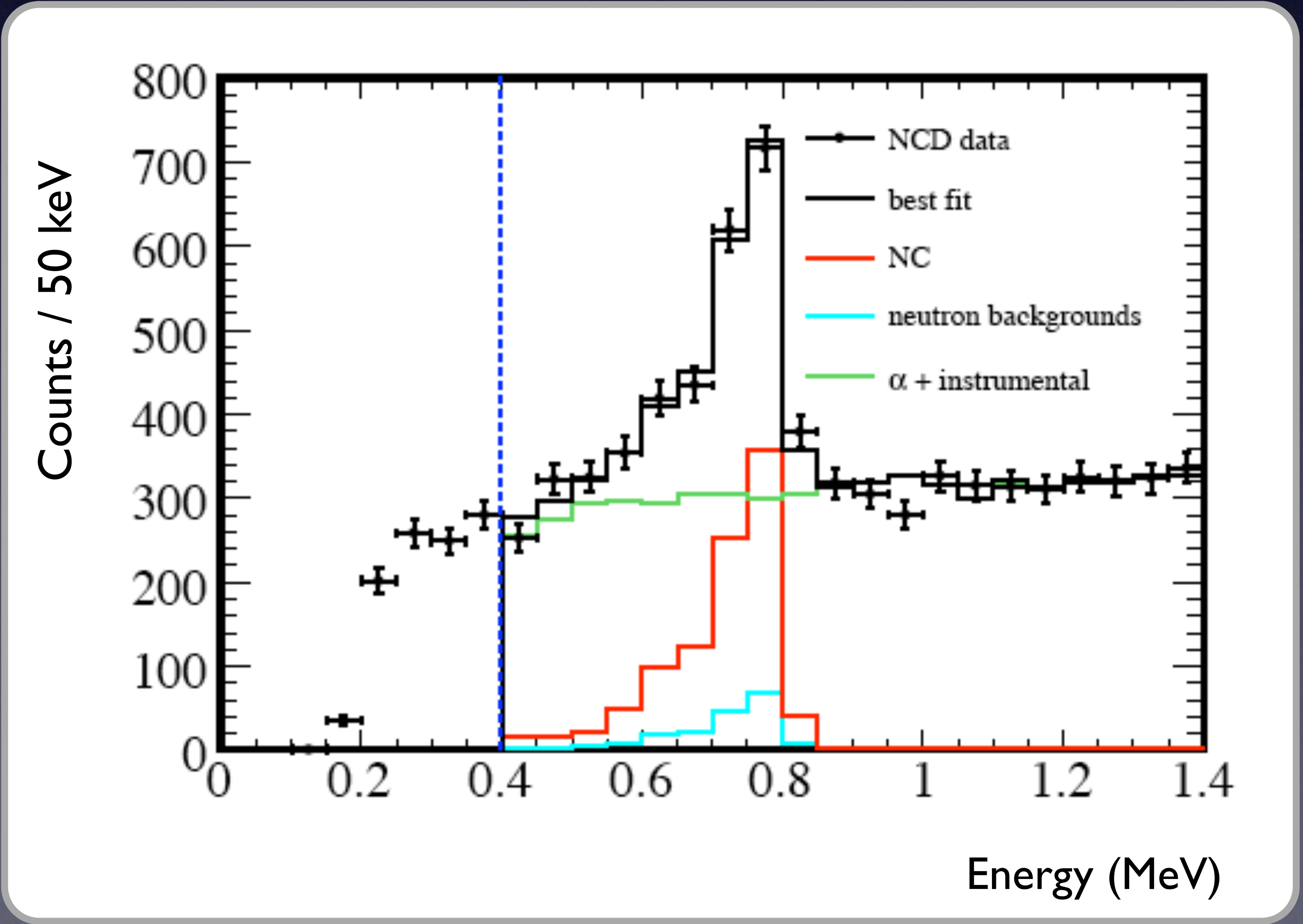

NCD

Neutral Current Signal:
983 ± 77

Neutron background:
185 ± 25

Alphas and Instrumentals:
6126 ± 250
(0.4 to 1.4 MeV)

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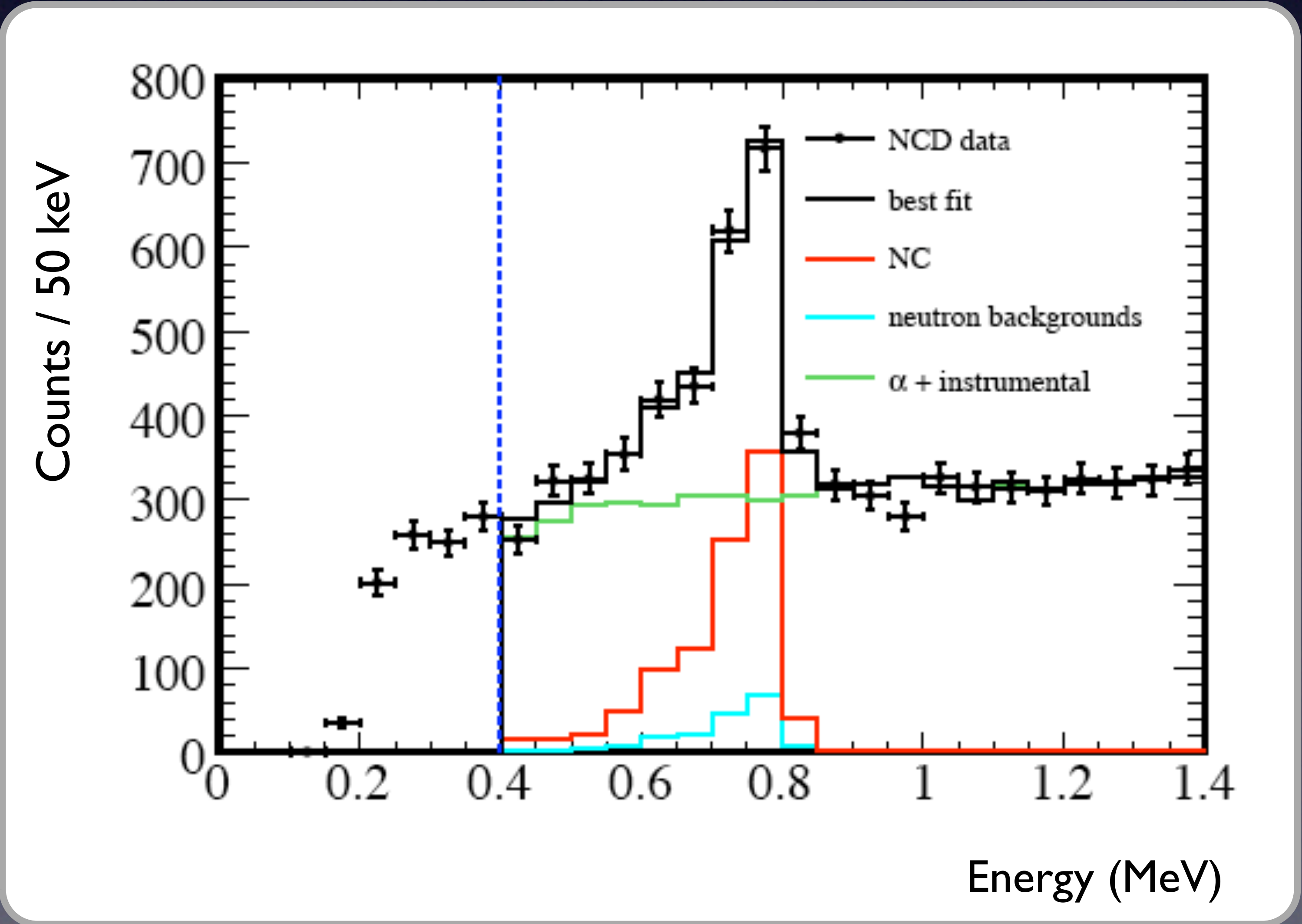

NCD

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983 ± 77

Neutron background:
185 ± 25

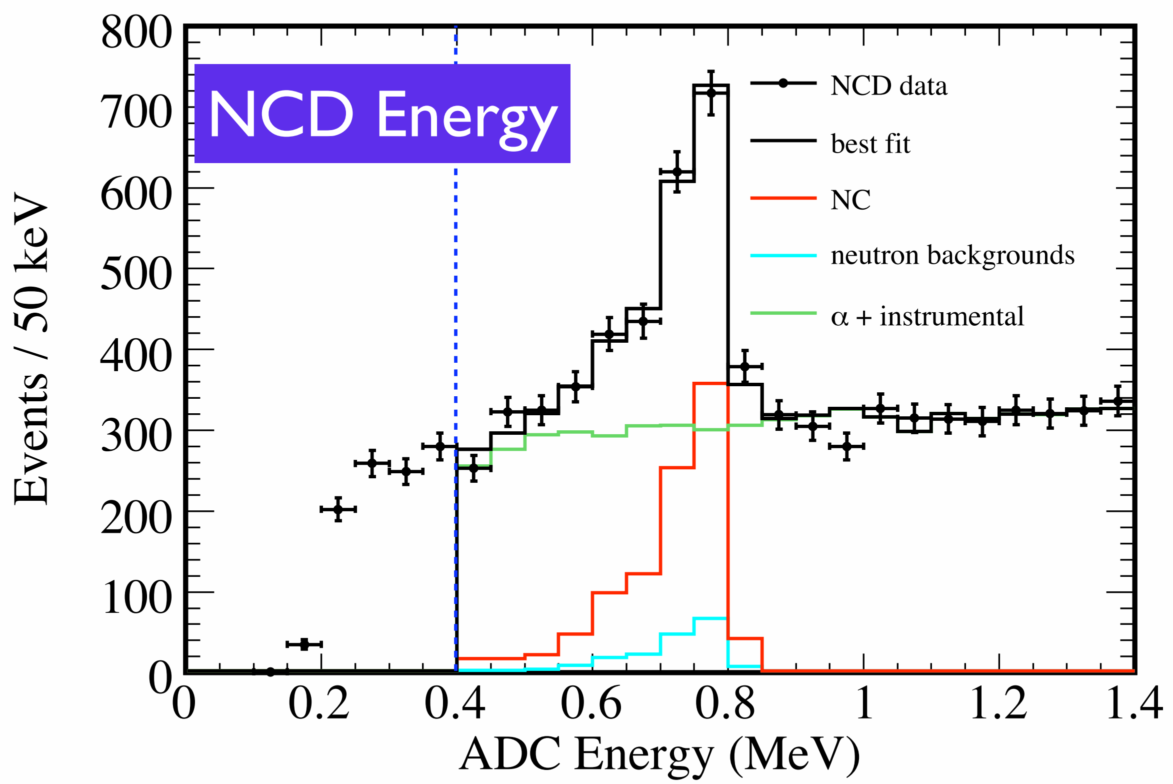
Alphas and Instrumentals:
6126 ± 250
(0.4 to 1.4 MeV)

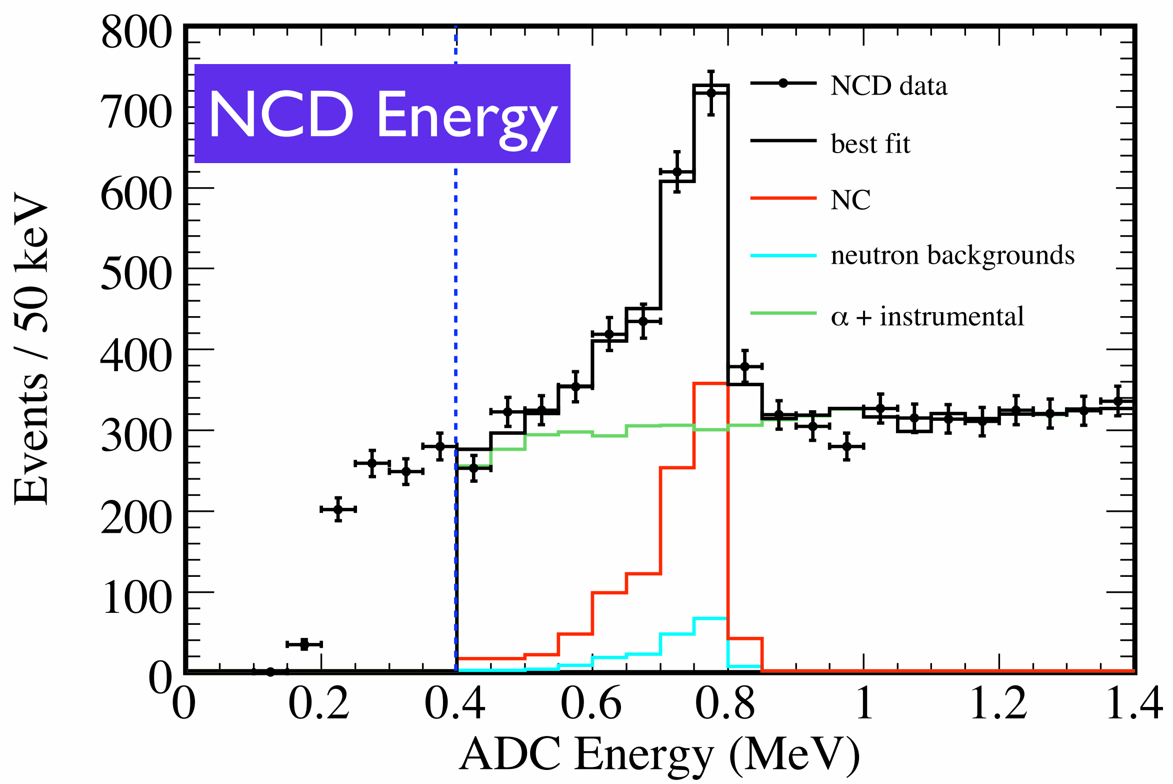
PMT

Charged Current Signal:
1867 ± 104

Neutral Background:
77 ± 12

Neutral Current Signal:
267 ± 24


NCD Energy
NCD data
best fit
NC
neutron backgrounds
α + instrumental
Events / 50 keV
ADC Energy (MeV)
0
100
200
300
400
500
600
700
800
0.2
0.4
0.6
0.8
1
1.2
1.4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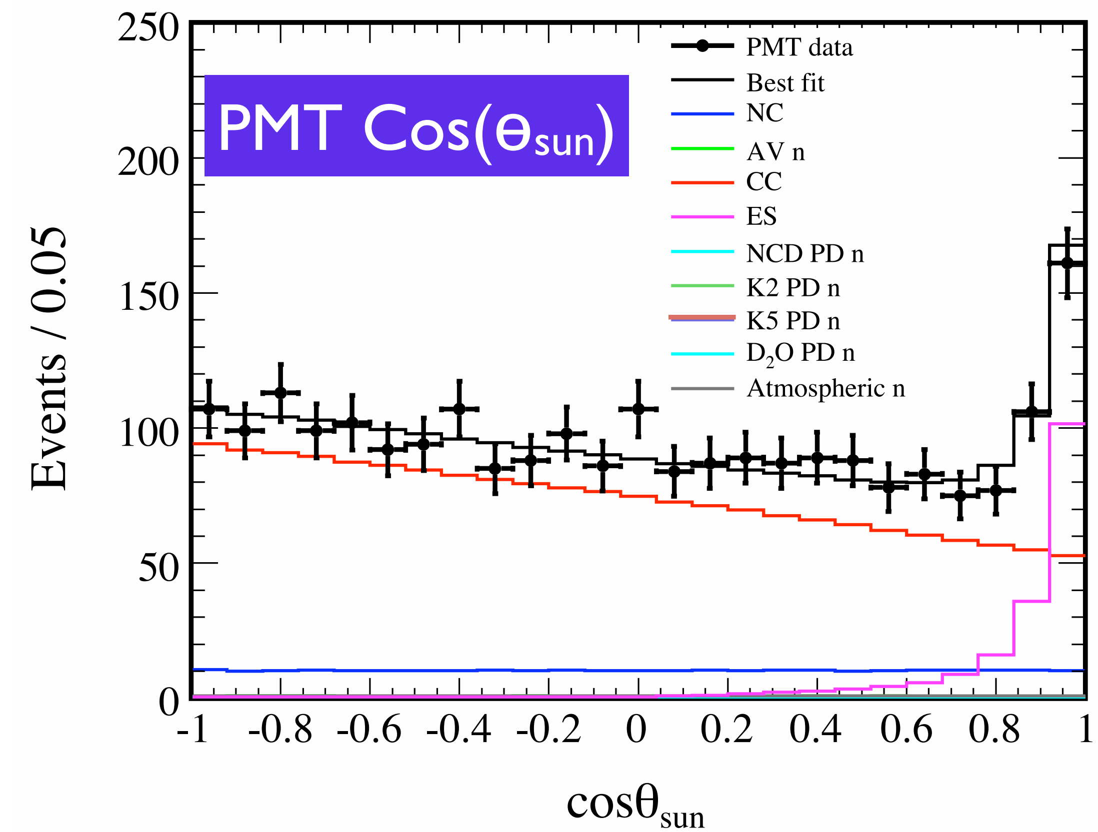
PMT Cos(θsun)
Events / 0.05
cosθsun
PMT data
Best fit
NC
AV n
CC
ES
NCD PD n
K2 PD n
K5 PD n
D2O PD n
Atmospheric n
0
50
100
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-0.8
-0.6
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-0.2
0
0.2
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0.6
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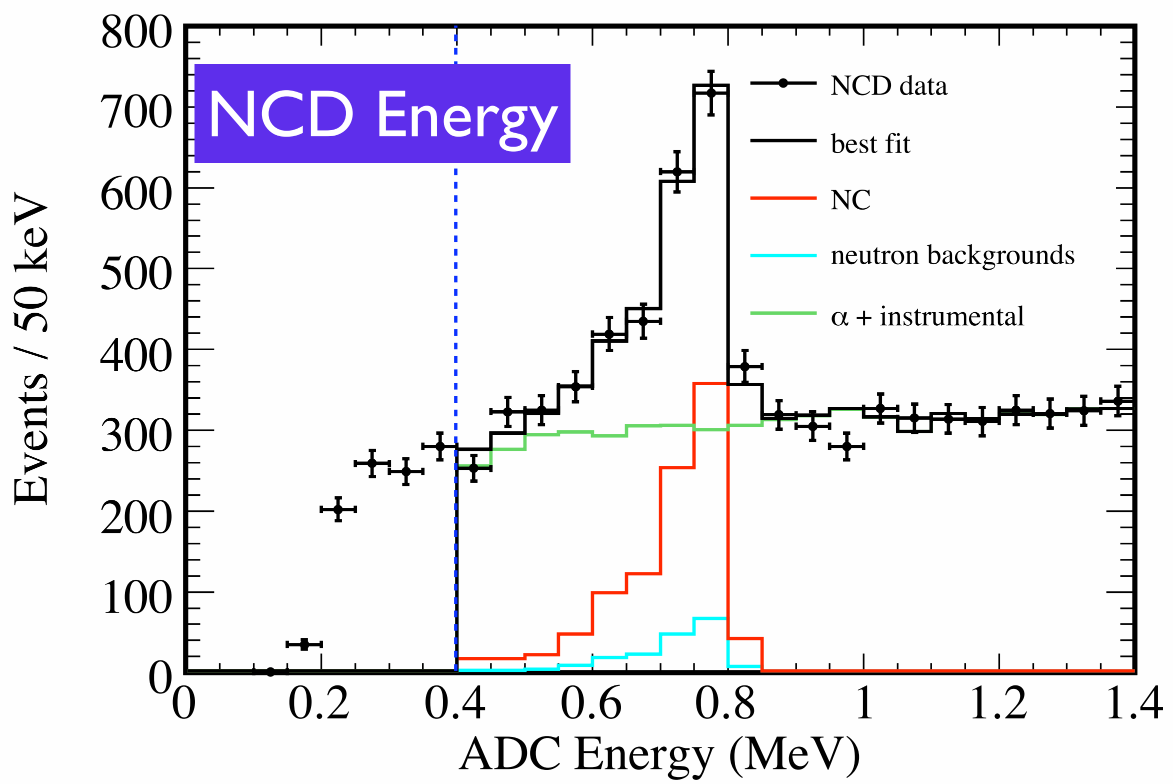
1


NCD Energy
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ADC Energy (MeV)
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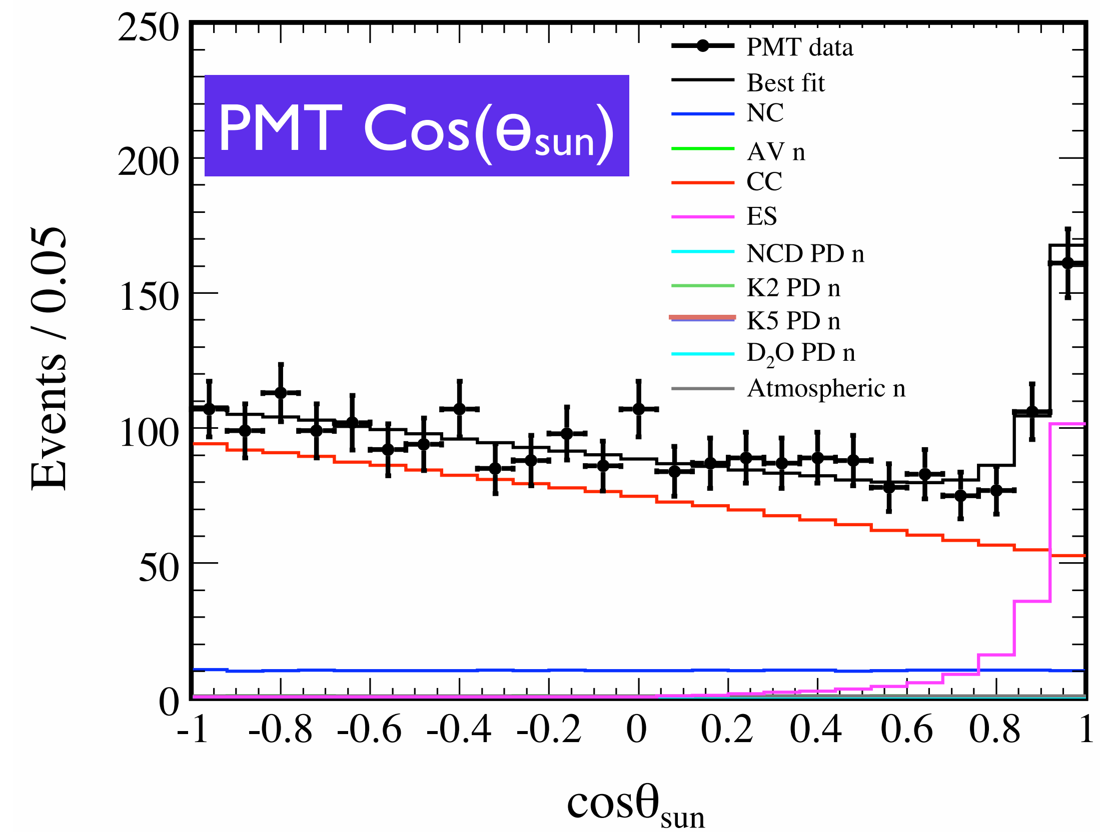
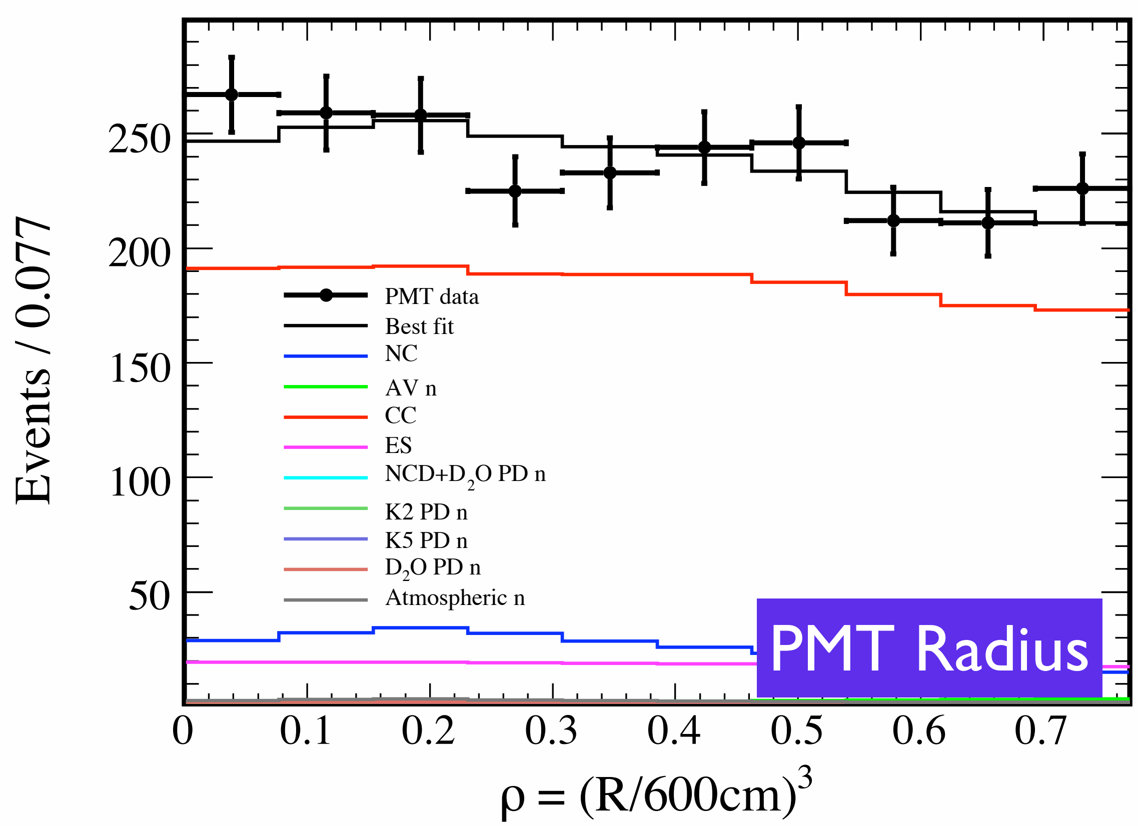
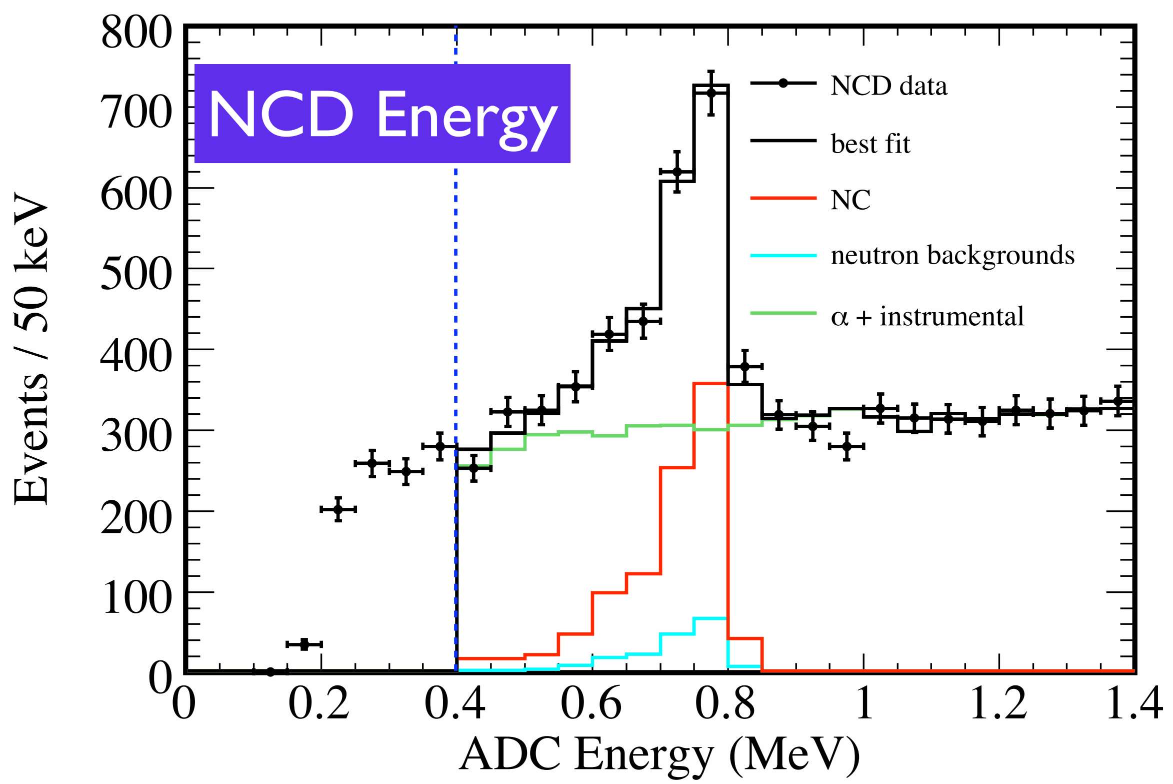
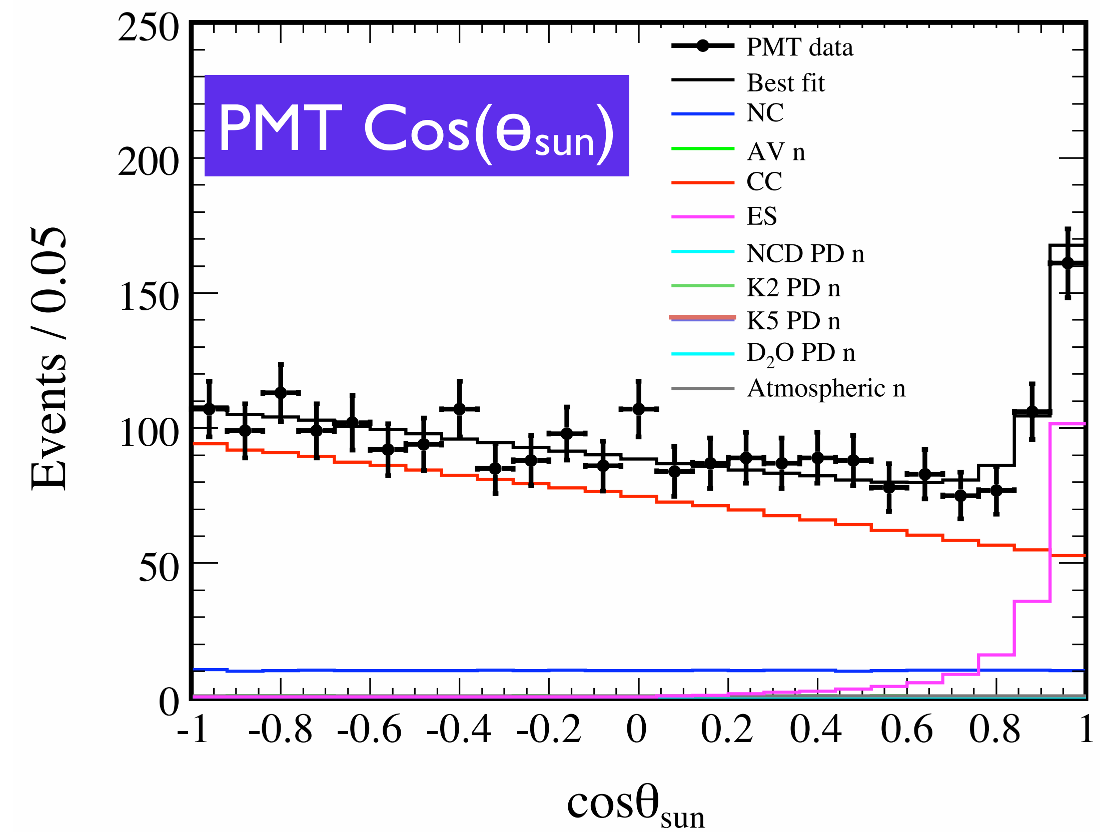
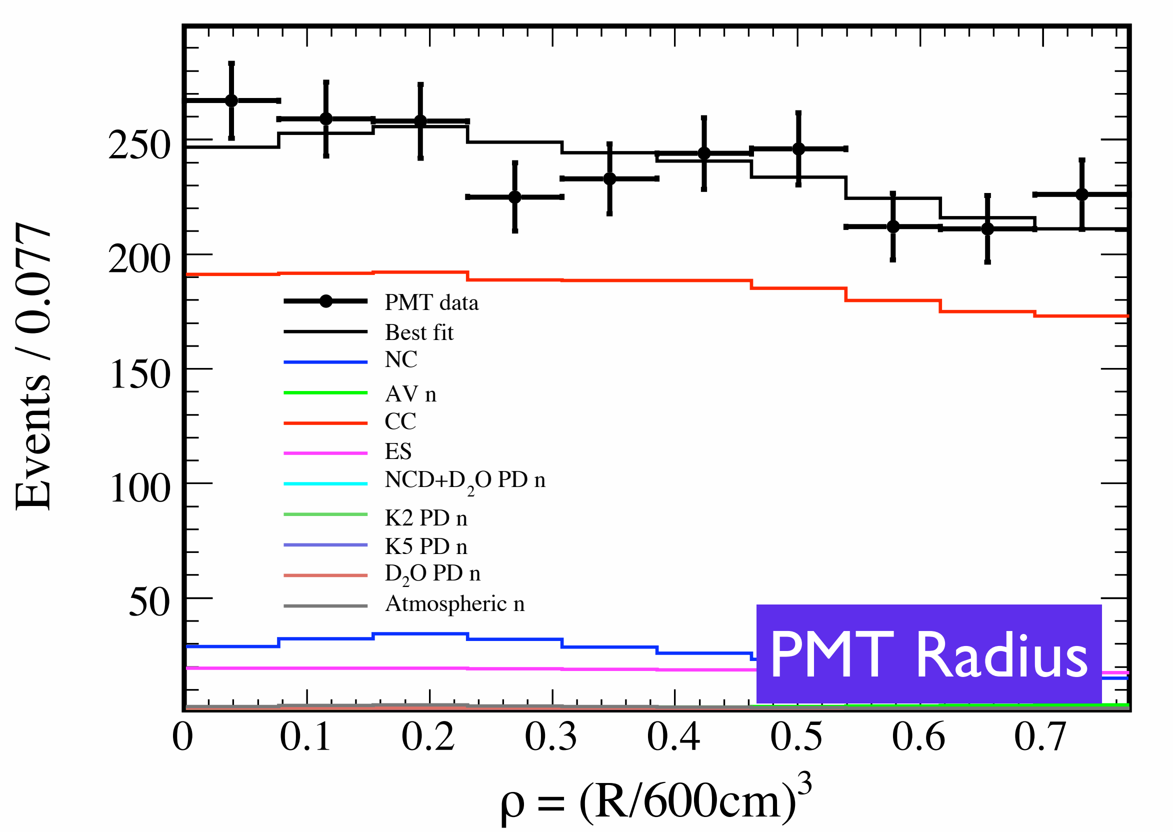
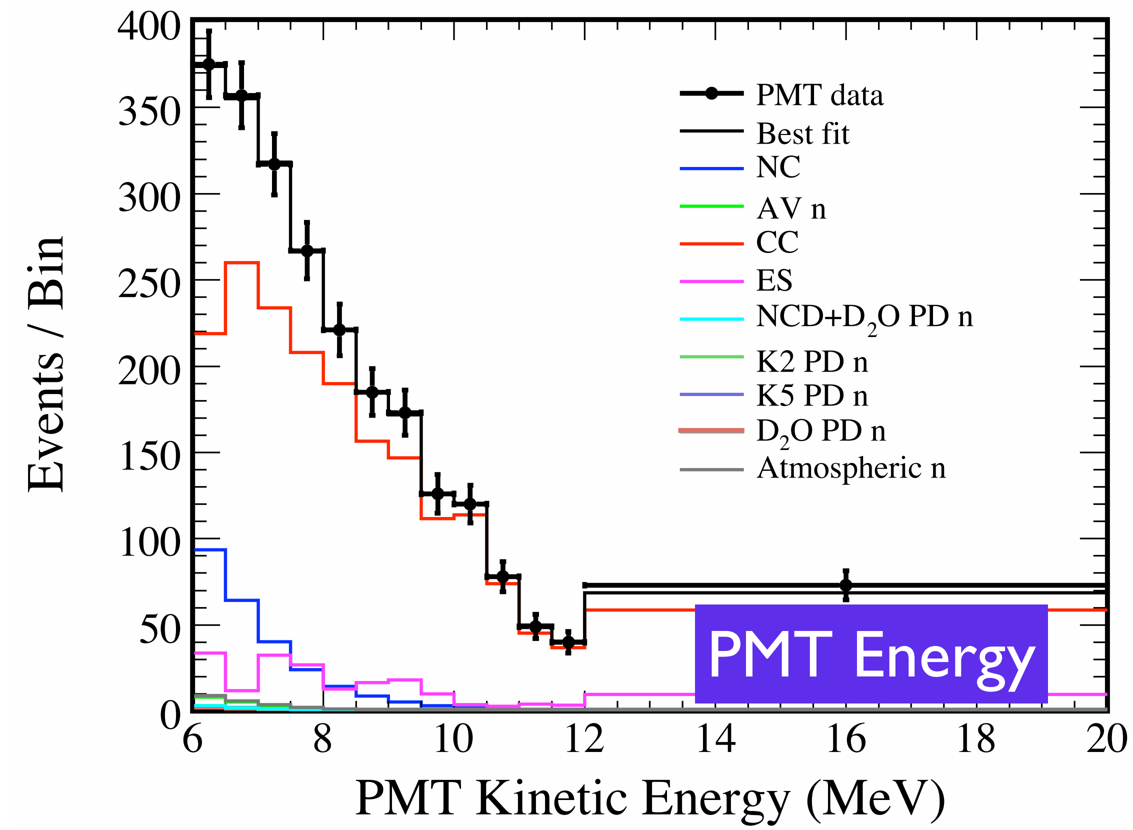

PMT Cos(θsun)
Events / 0.05
cosθsun
PMT data
Best fit
NC
AV n
CC
ES
NCD PD n
K2 PD n
K5 PD n
D2O PD n
Atmospheric n
0
50
100
150
200
250
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


PMT Radius
Events / 0.077
ρ = (R/600cm)^3
PMT data
Best fit
NC
AV n
CC
ES
NCD+D2O PD n
K2 PD n
K5 PD n
D2O PD n
Atmospheric n
50
100
150
200
250
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


NCD Energy
NCD data
best fit
NC
neutron backgrounds
α + instrumental
Events / 50 keV
ADC Energy (MeV)
0
100
200
300
400
500
600
700
800
0.2
0.4
0.6
0.8
1
1.2
1.4


PMT Cos(θsun)
PMT data
Best fit
NC
AV n
CC
ES
NCD PD n
K2 PD n
K5 PD n
D_2O PD n
Atmospheric n
Events / 0.05
cosθsun
0
50
100
150
200
250
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


PMT Radius
PMT data
Best fit
NC
AV n
CC
ES
NCD+D_2O PD n
K2 PD n
K5 PD n
D_2O PD n
Atmospheric n
Events / 0.077
$\rho = (R/600cm)^3$
50
100
150
200
250
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


PMT Energy
PMT data
Best fit
NC
AV n
CC
ES
NCD+D_2O PD n
K2 PD n
K5 PD n
D_2O PD n
Atmospheric n
Events / Bin
PMT Kinetic Energy (MeV)
0
50
100
150
200
250
300
350
400
6
8
10
12
14
16
18
20

Measured Fluxes

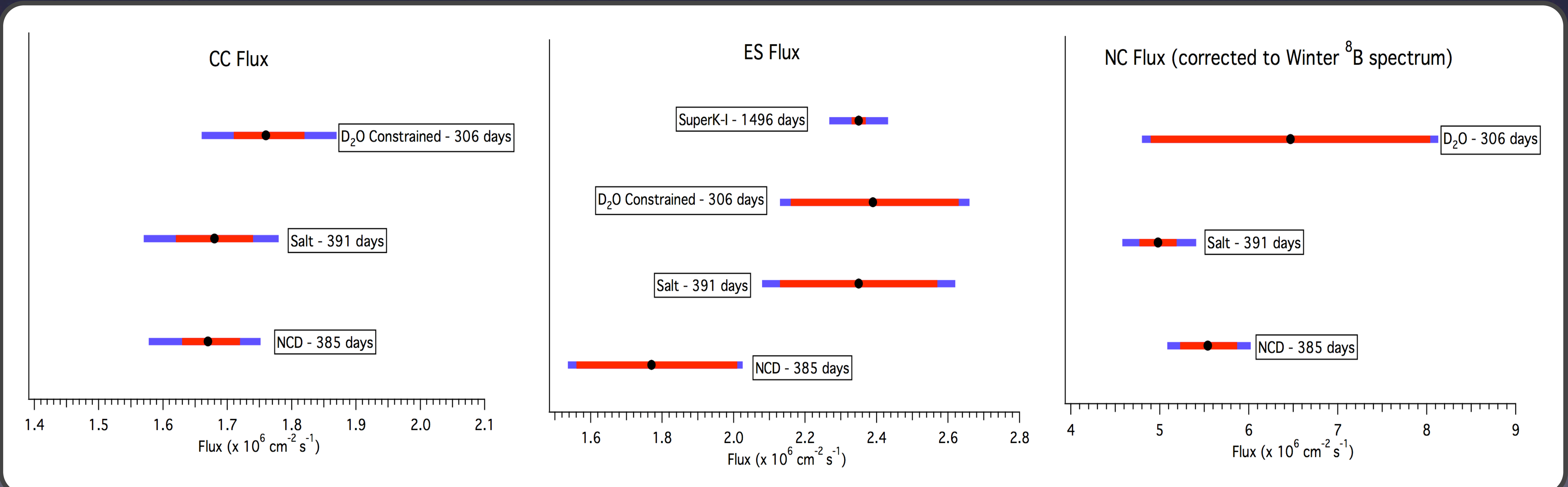
Reaction	Flux (x 10^6 cm^{-2} s^{-1})
Charged Current	$1.67^{+0.05}_{-0.04}$ (stat) $^{+0.07}_{-0.08}$ (sys)
Elastic Scattering	$1.77^{+0.24}_{-0.21}$ (stat) $^{+0.09}_{-0.10}$ (sys)
Neutral Current	$5.54^{+0.33}_{-0.31}$ (stat) $^{+0.36}_{-0.34}$ (sys)

NCD Phase

Perform combined fit of NCD neutrons and PMT observables to extract CC, NC, and ES fluxes.

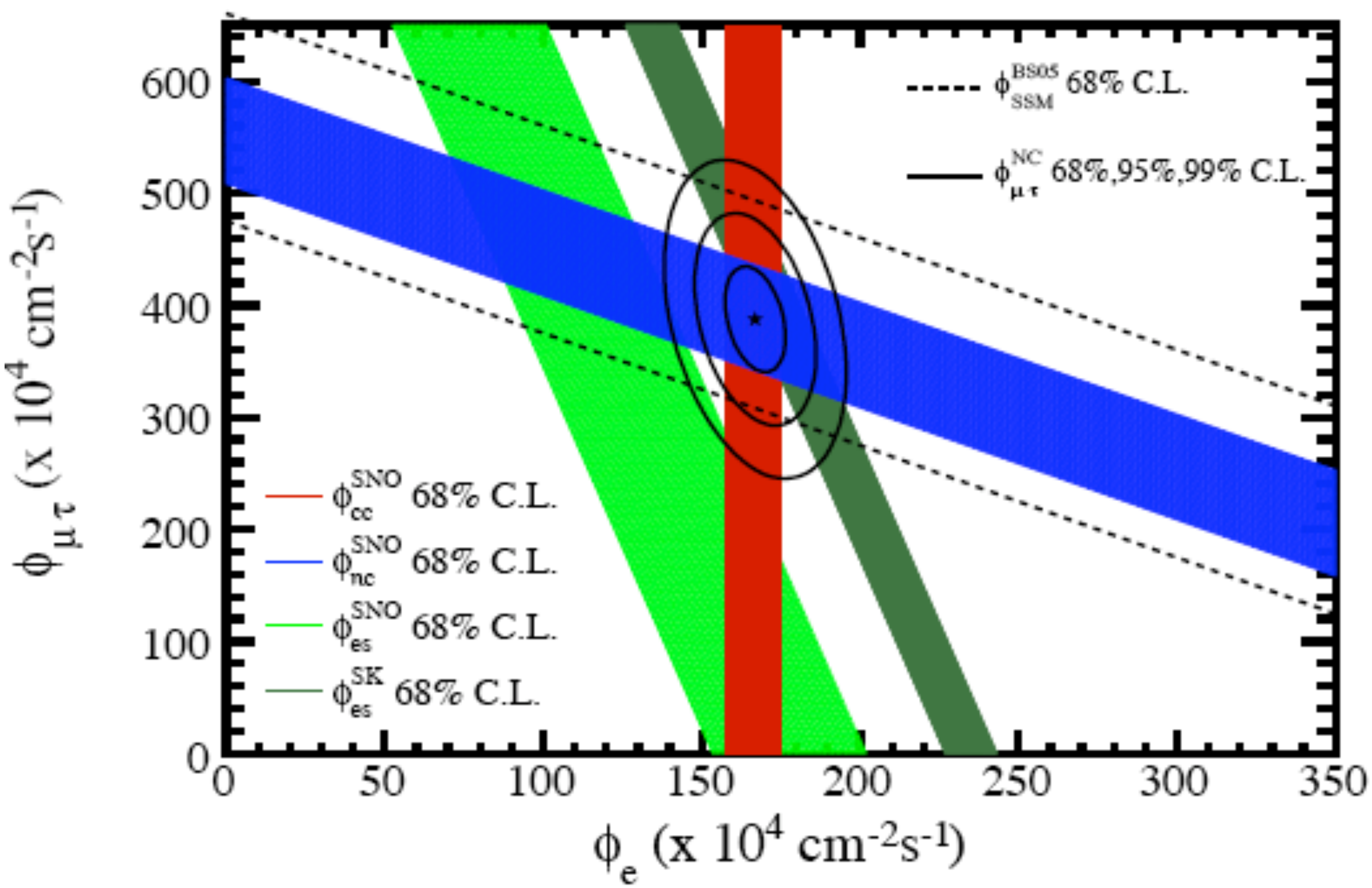
Overall p-value across phases and fluxes is 32.8%

Across all phases



Results from the NCD Phase

$$\frac{\phi_{\rm CC}}{\phi_{\rm NC}} = 0.301 \pm 0.033 = \cos^4(\theta_{13}) \sin^2(\theta_{12})$$



SNO Collaboration, arXiv:0806.0989
Submitted to Physical Review Letters

Fluxes

(10^6 cm^{-2} s^{-1})

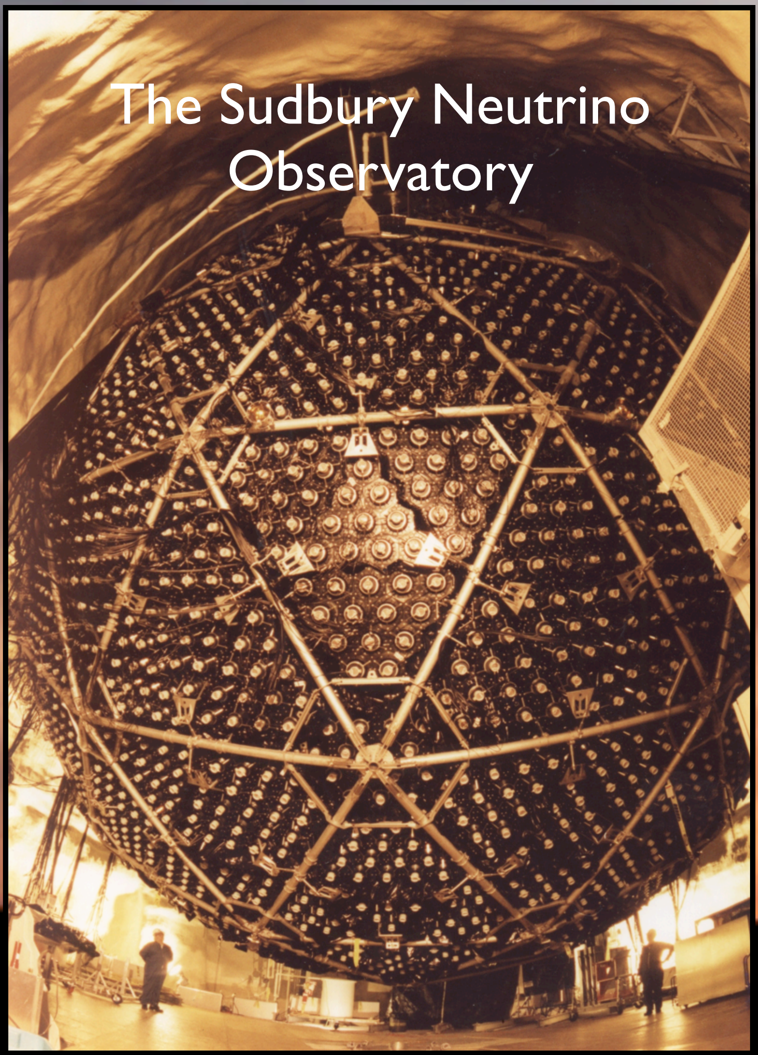
ν_e: 1.67 $\pm$ 0.09

ν_{ES}: 1.77 $\pm$ 0.26

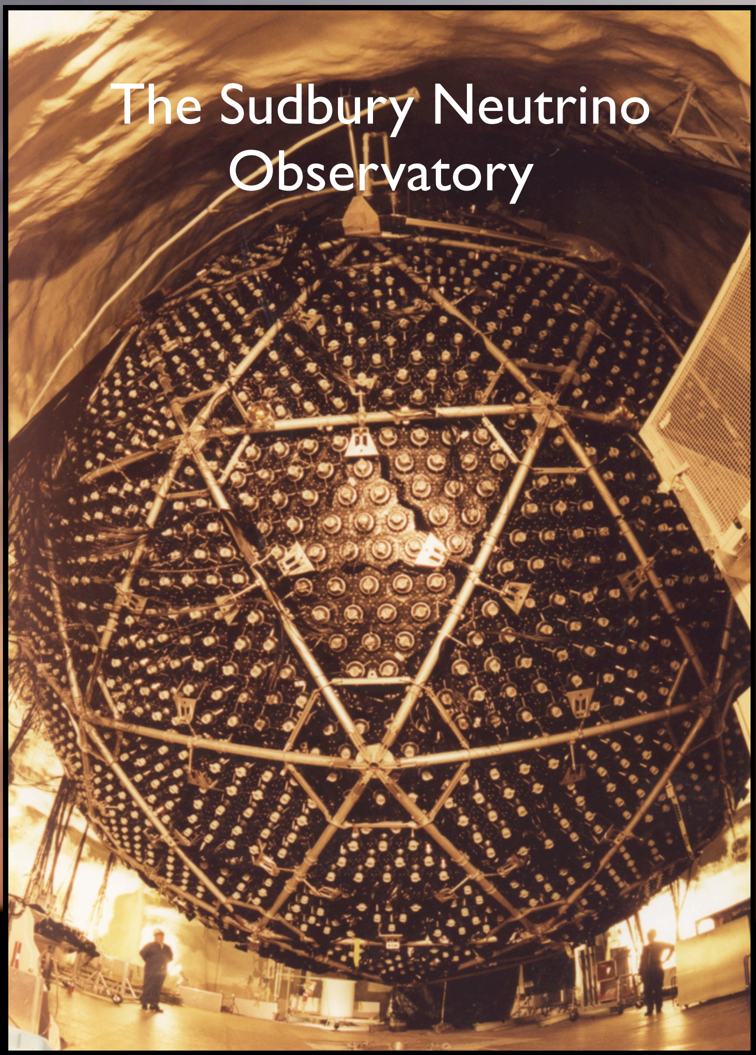
ν_{total}: 5.54 $\pm$ 0.48

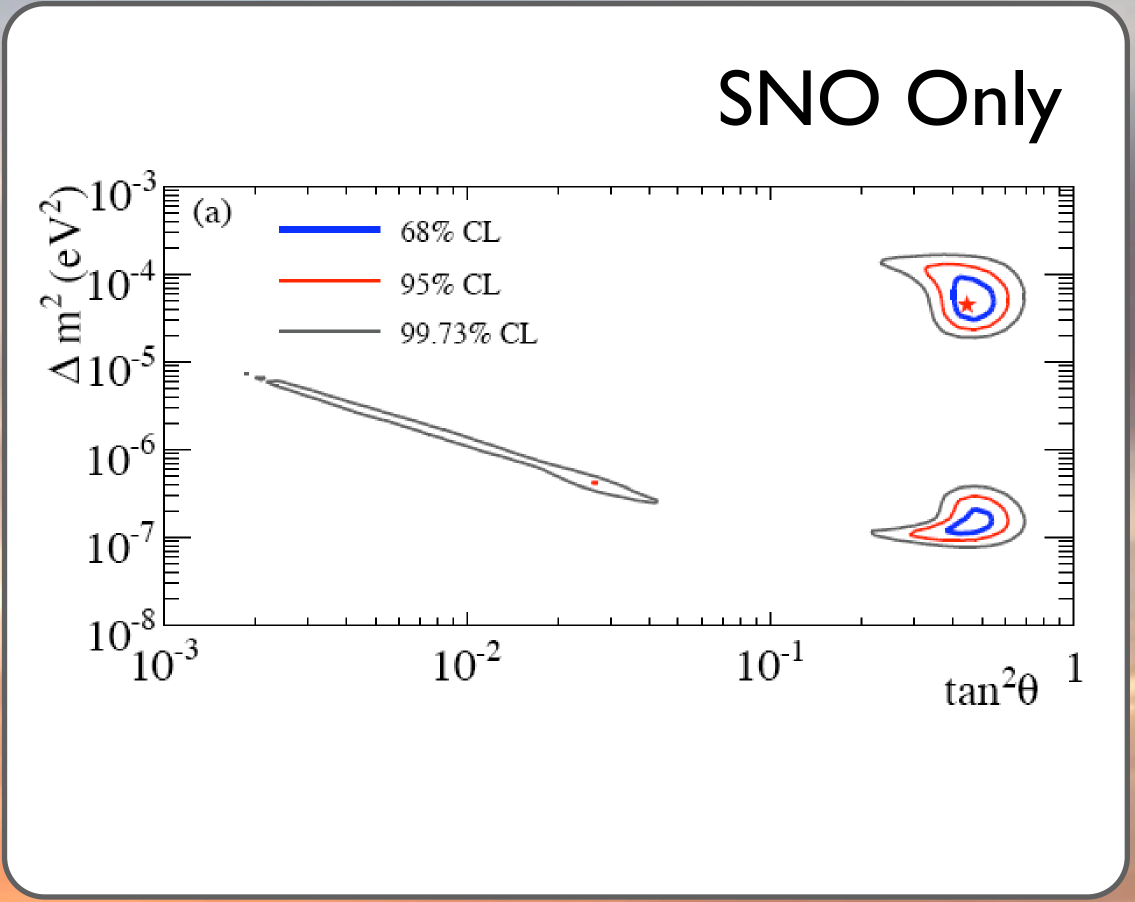
ν_{SSM05}: 5.69 $\pm$ 0.91

Neutrino Oscillations

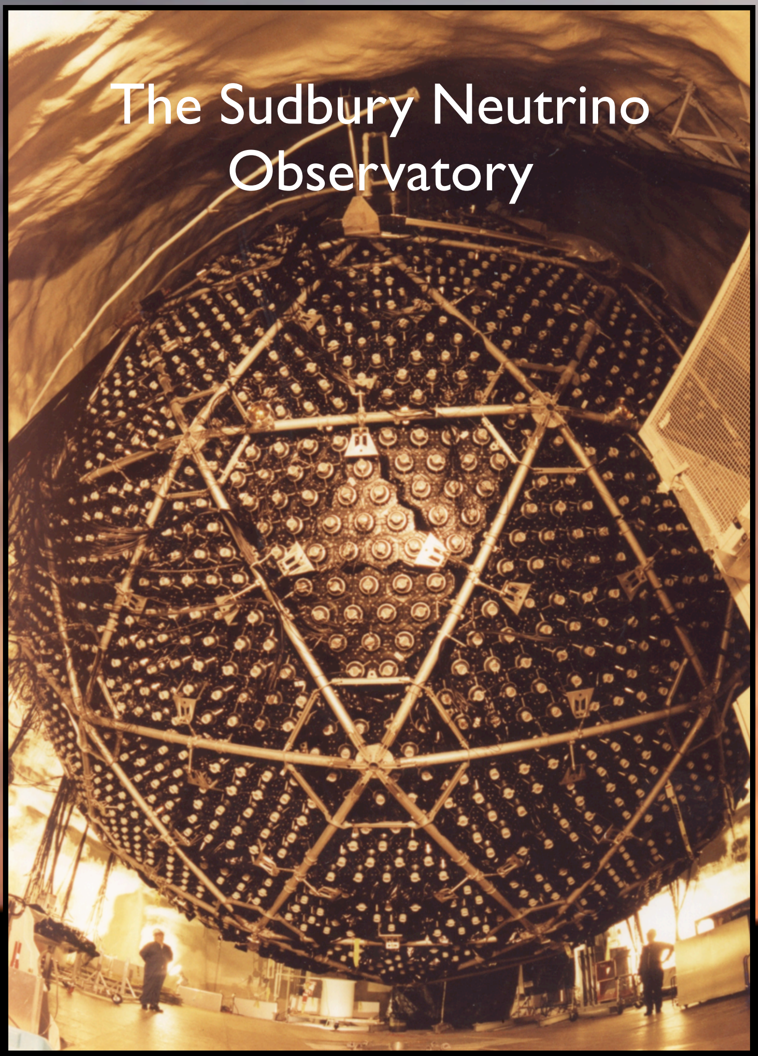


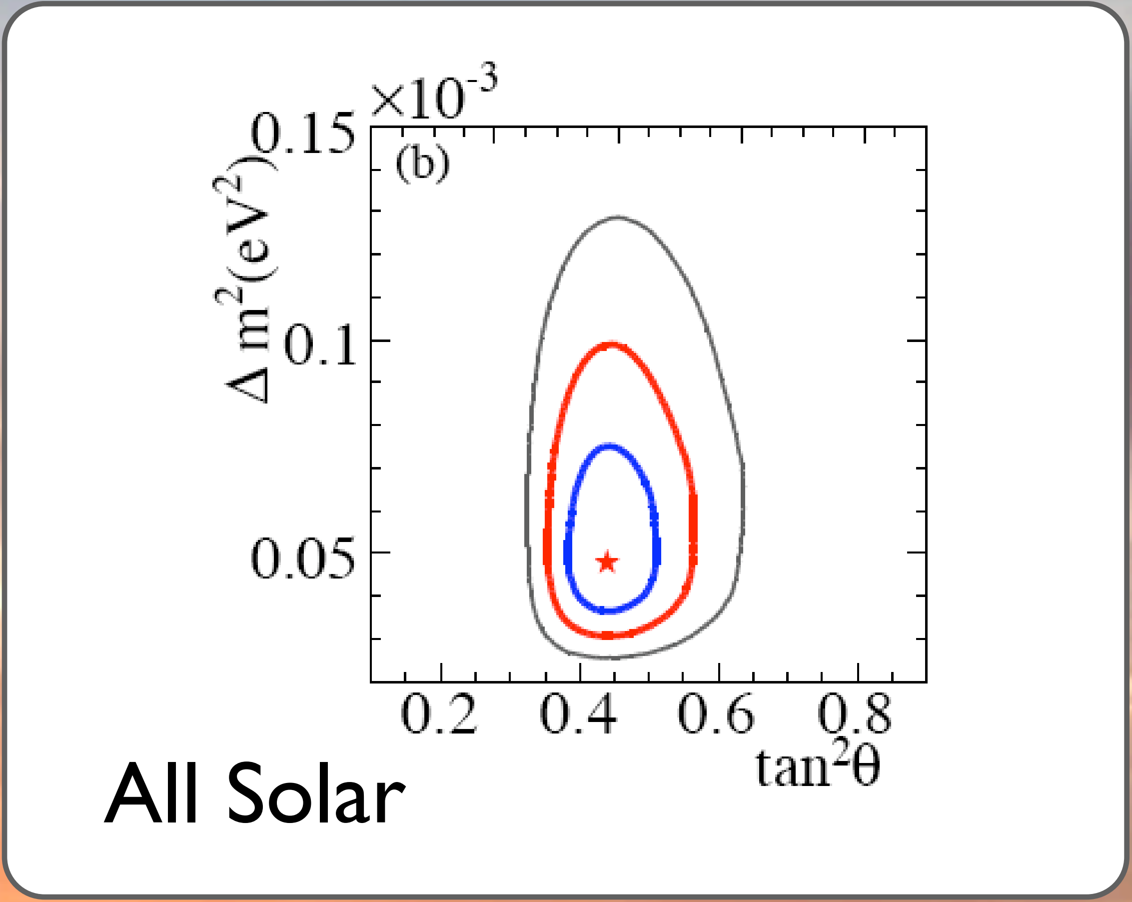
Neutrino Oscillations



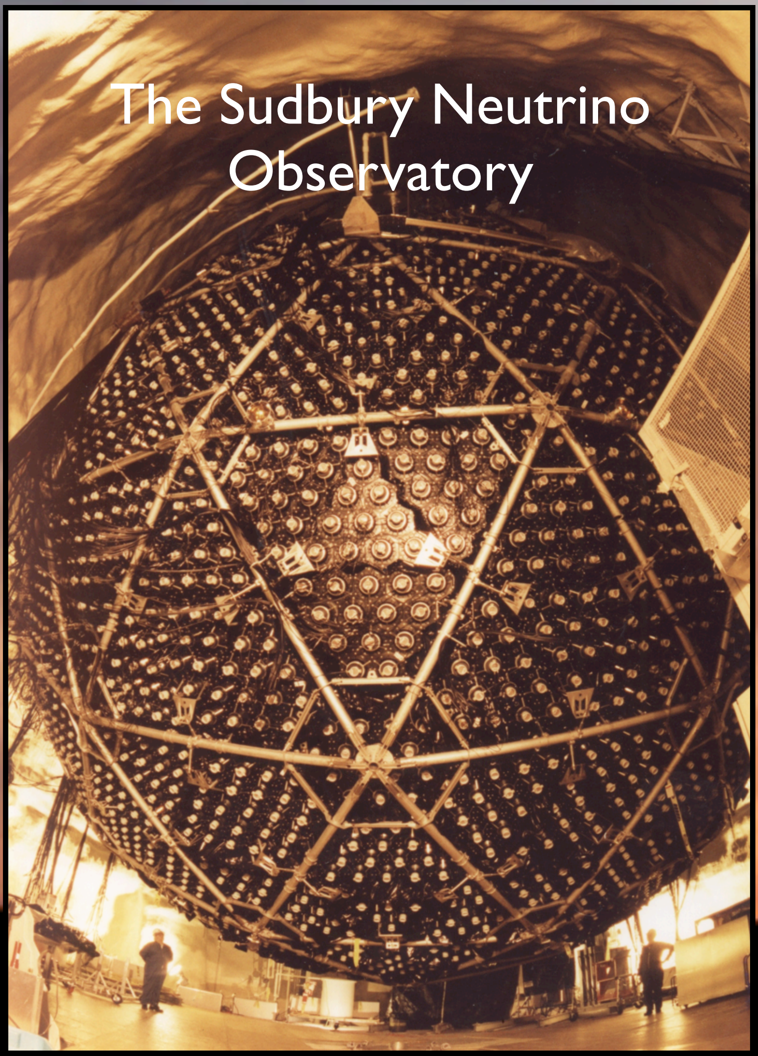


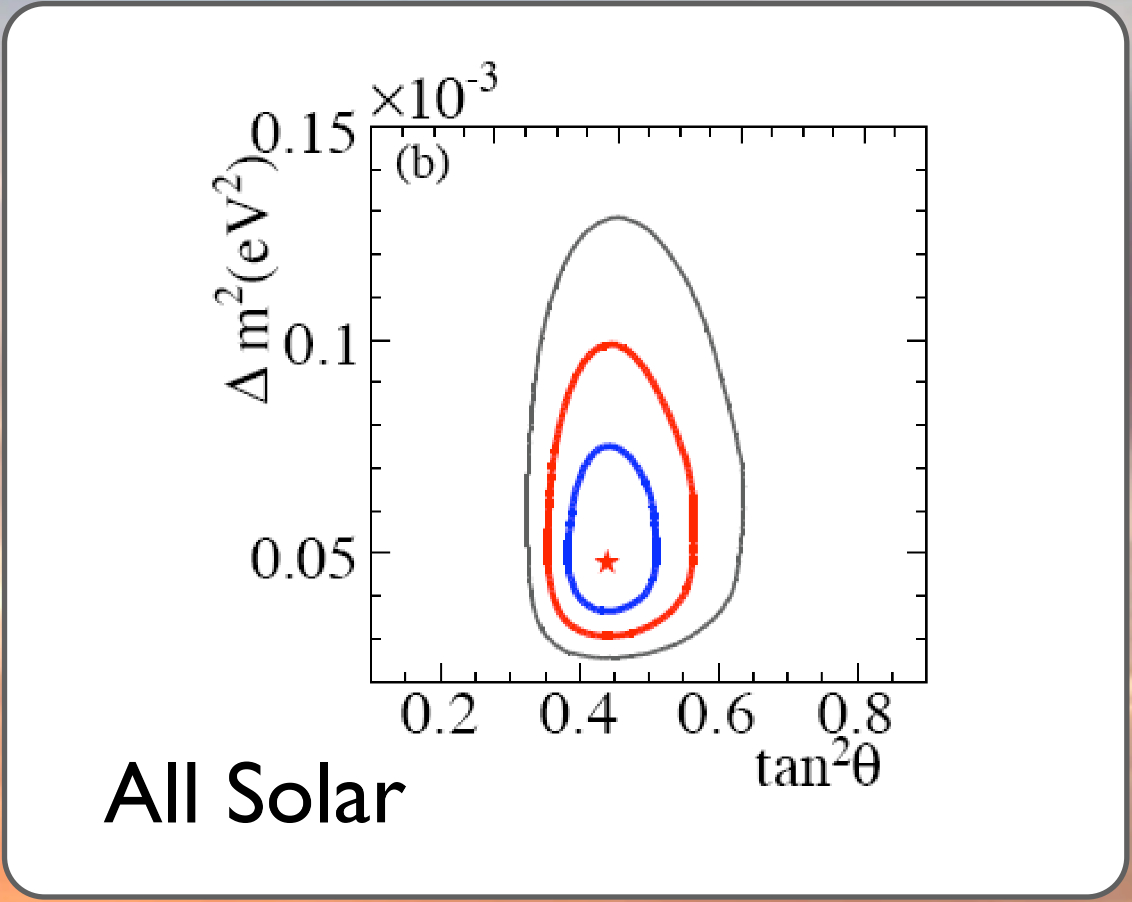
Neutrino Oscillations

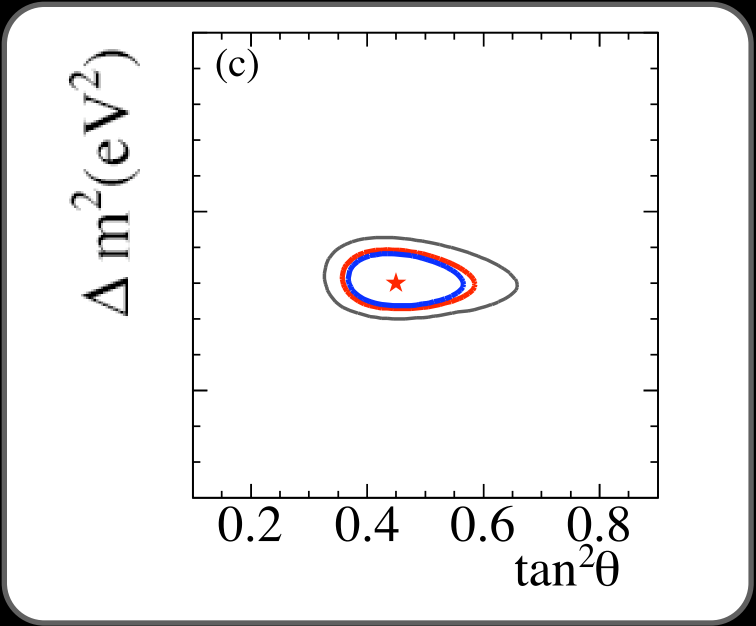


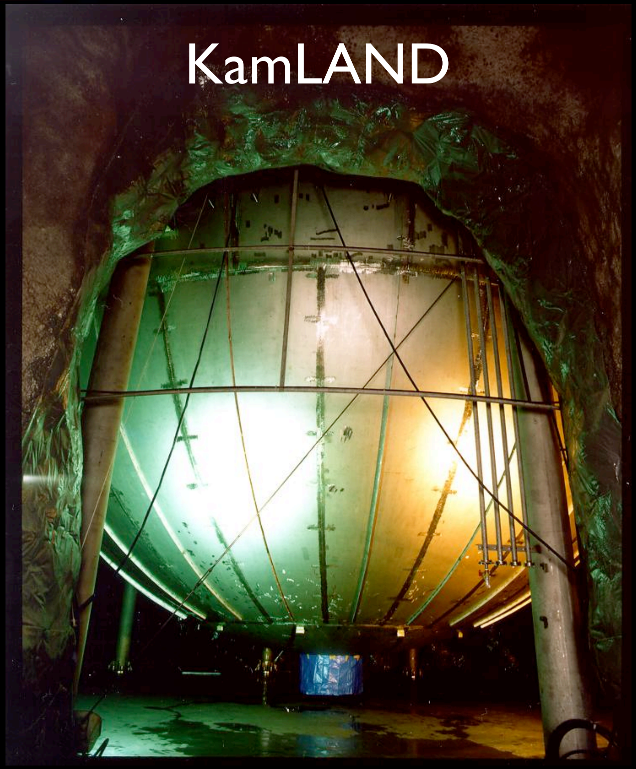


Neutrino Oscillations

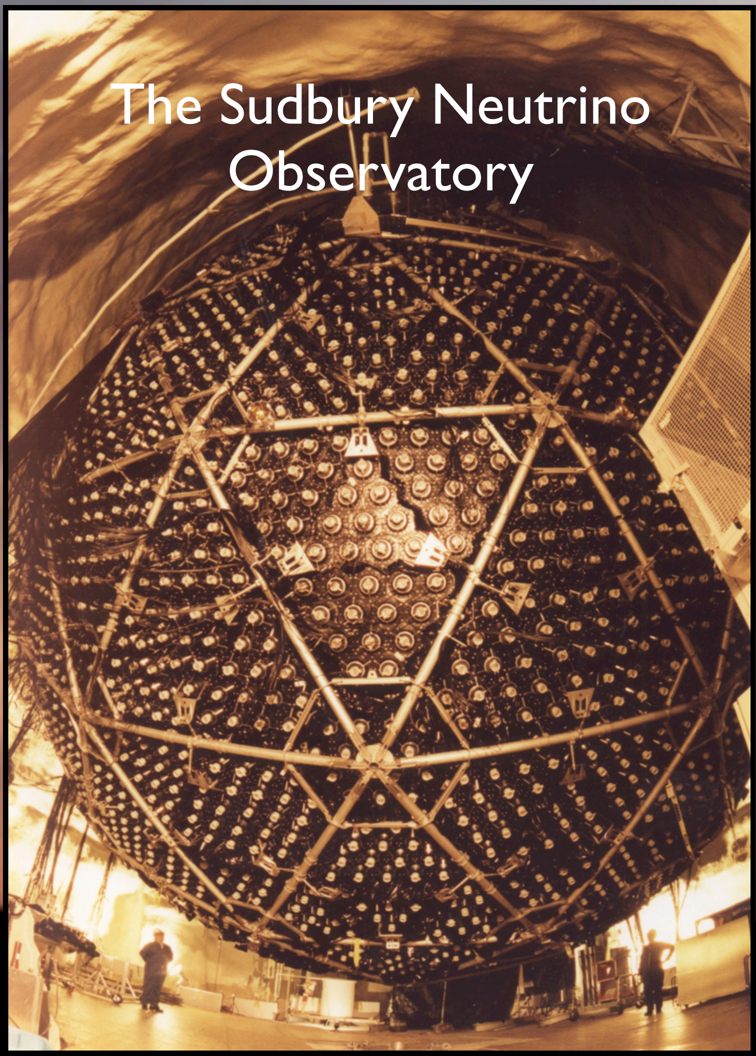


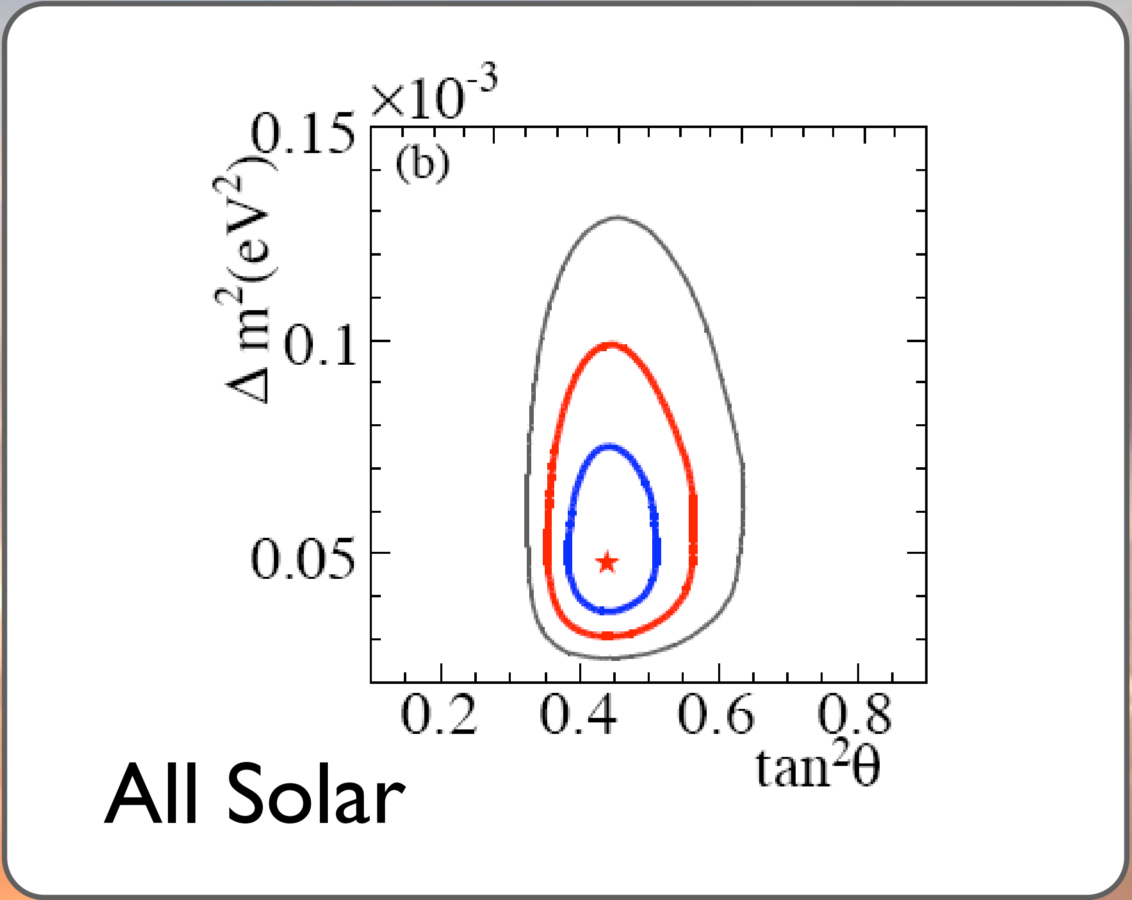






Neutrino Oscillations



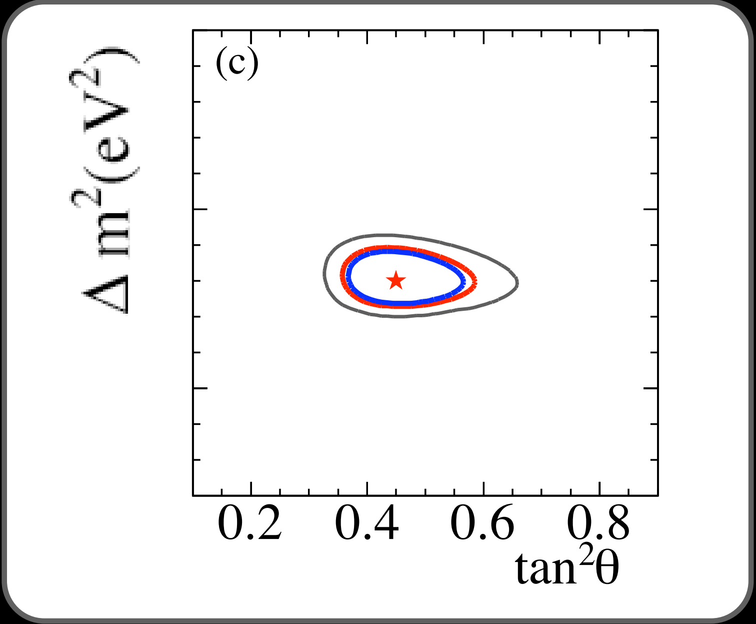


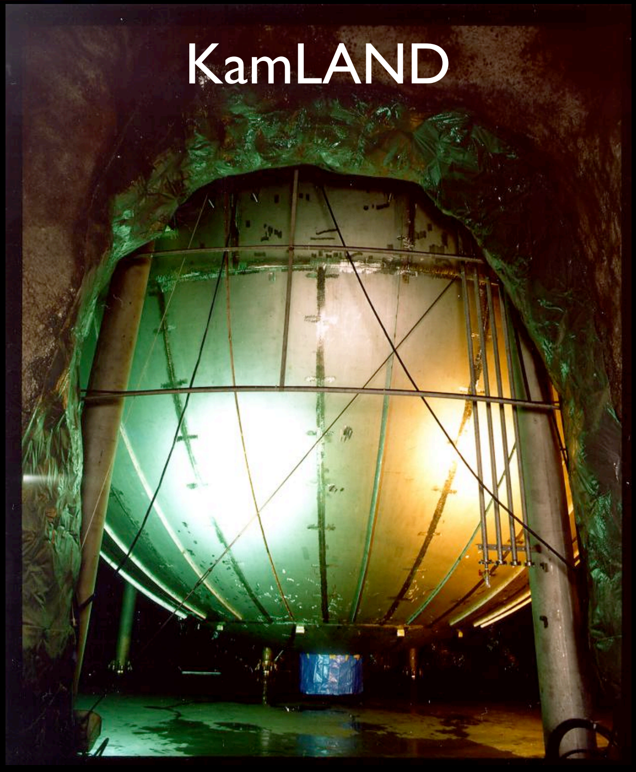
Best-fit Neutrino Parameters

Δm^2: $7.94\ ^{+0.42}_{-0.26} \times 10^{-5}\ \mathrm{eV}^2$

θ_{12}: $33.8\ ^{+1.4}_{-1.3}$ degrees

f_{8B}: 0.873



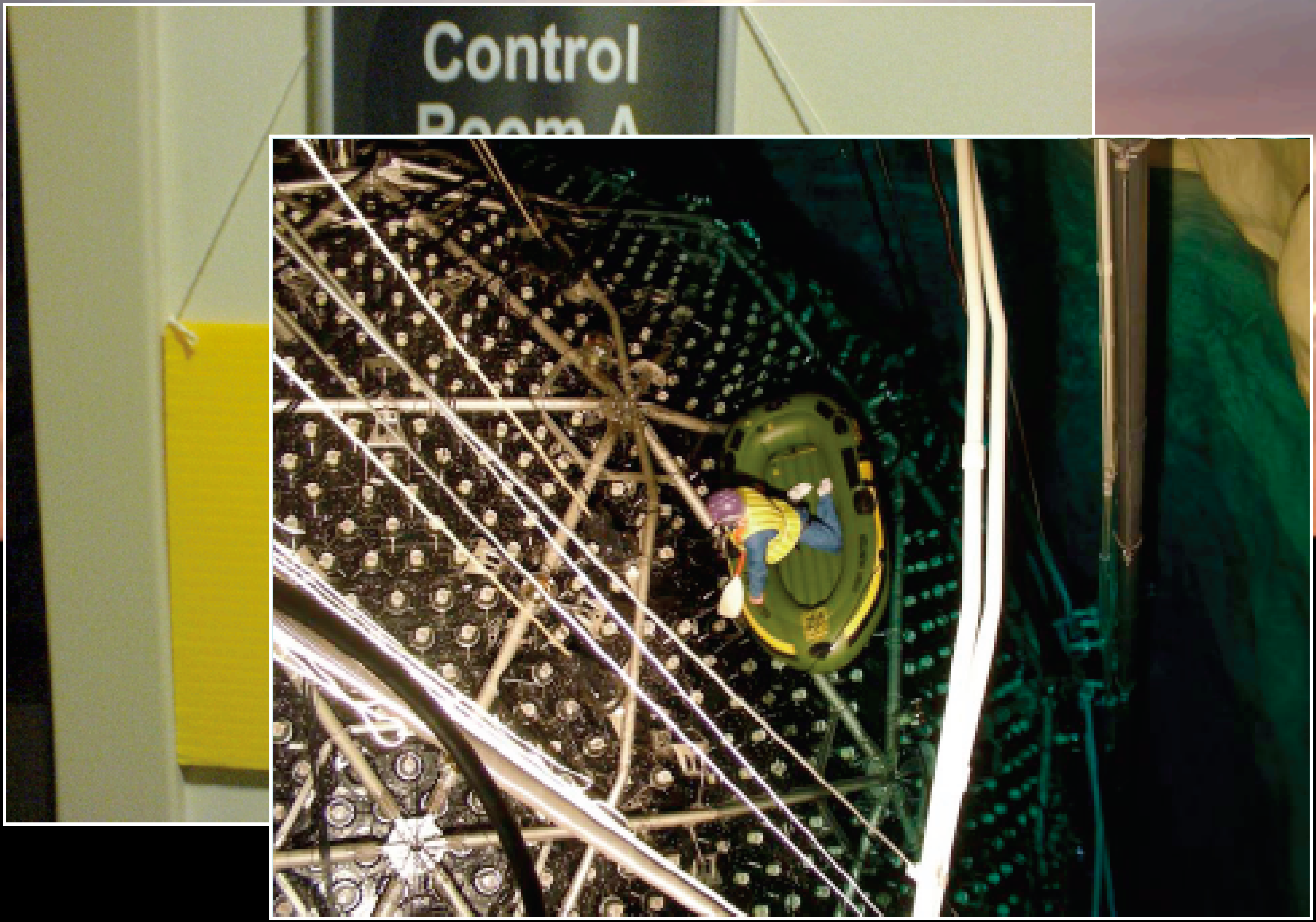



...so?
Is it over?

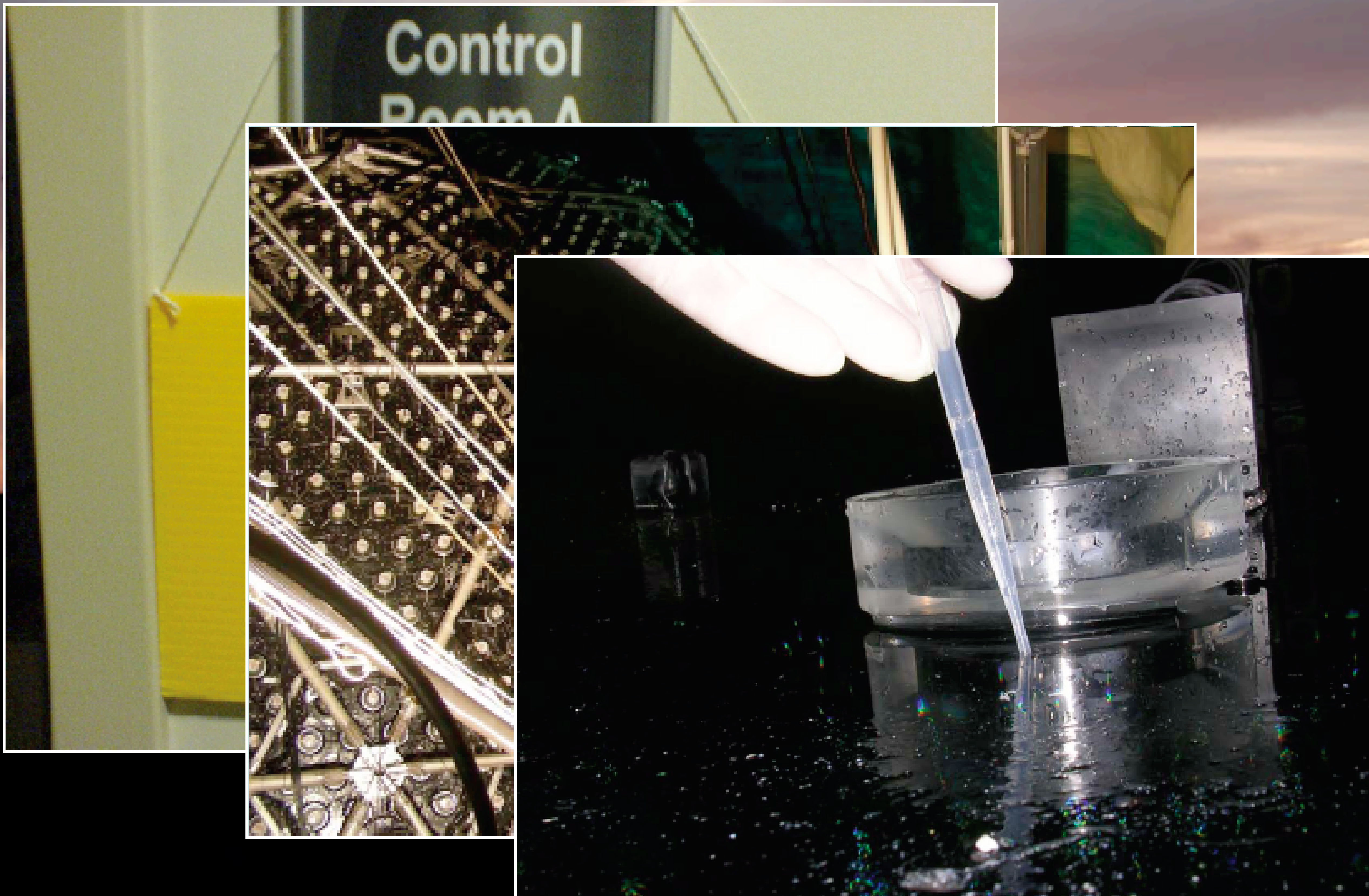

All good things...

All good things...

All good things...

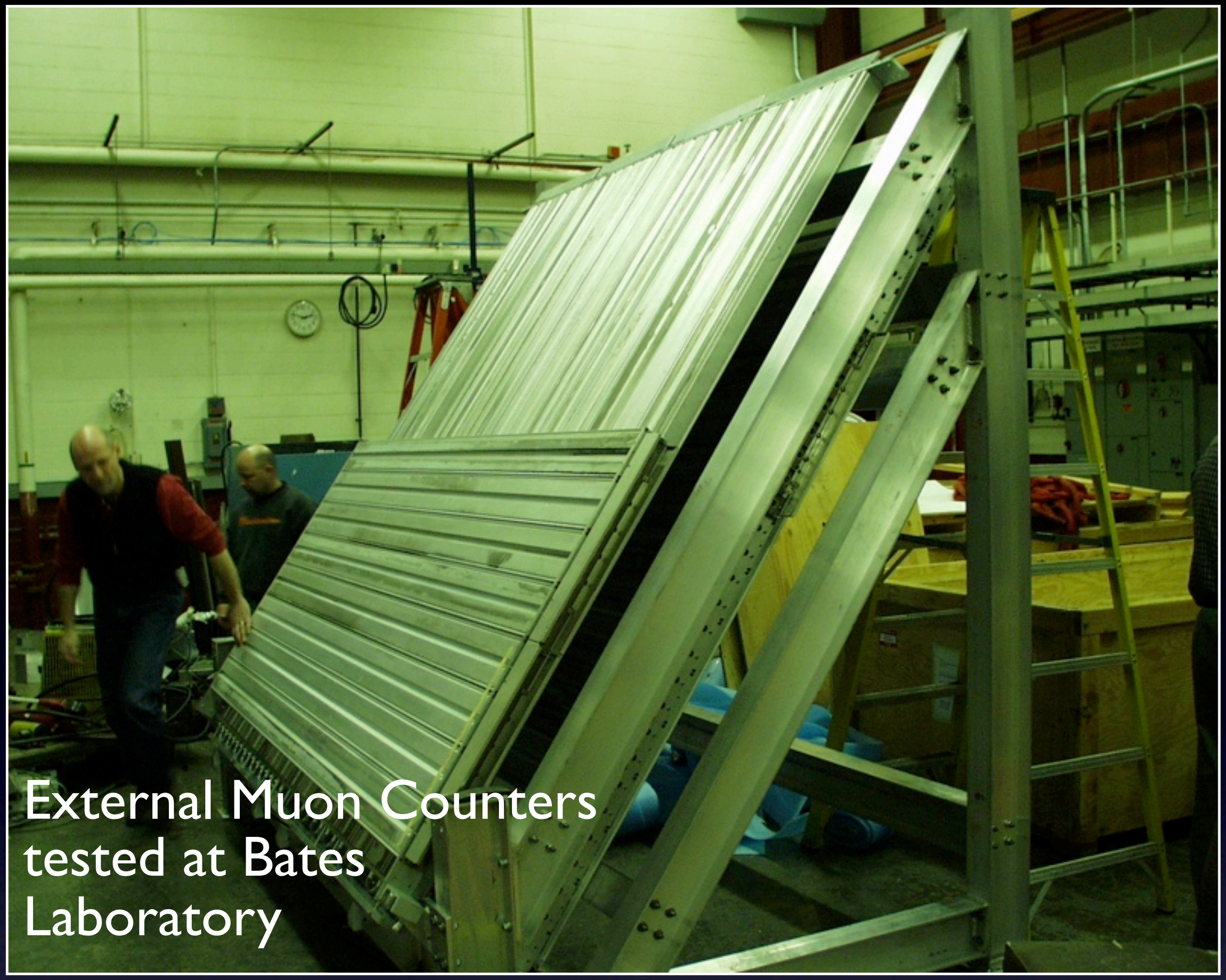


All good things...



...except, there's more physics...

...except, there's more physics...



Ongoing Analyses

(1) LETA analysis (low energy threshold analysis

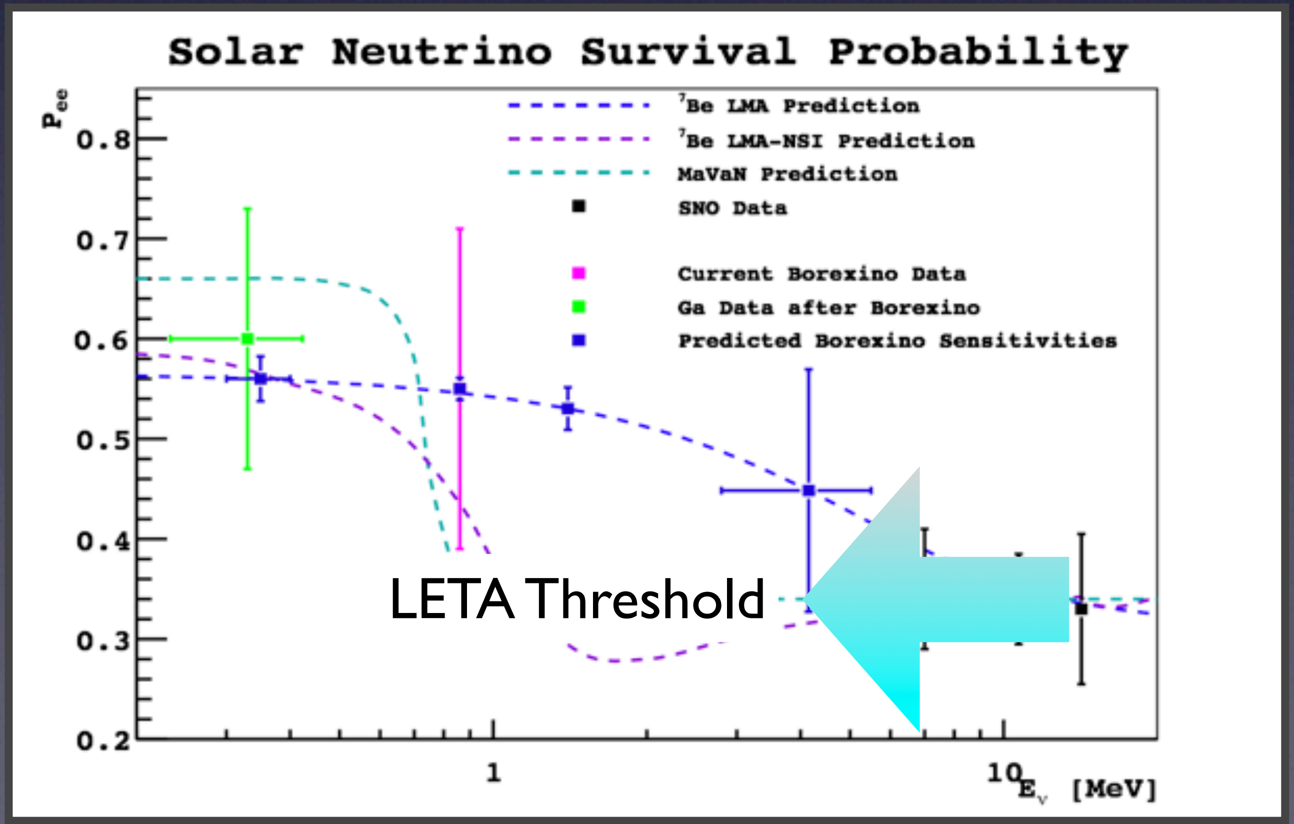
(2) Atmospheric neutrinos

(3) A full 3-phase analysis

(4) Day-night asymmetry

(5) "Exotica" (n-nbar oscillations, dark matter, burst searches)

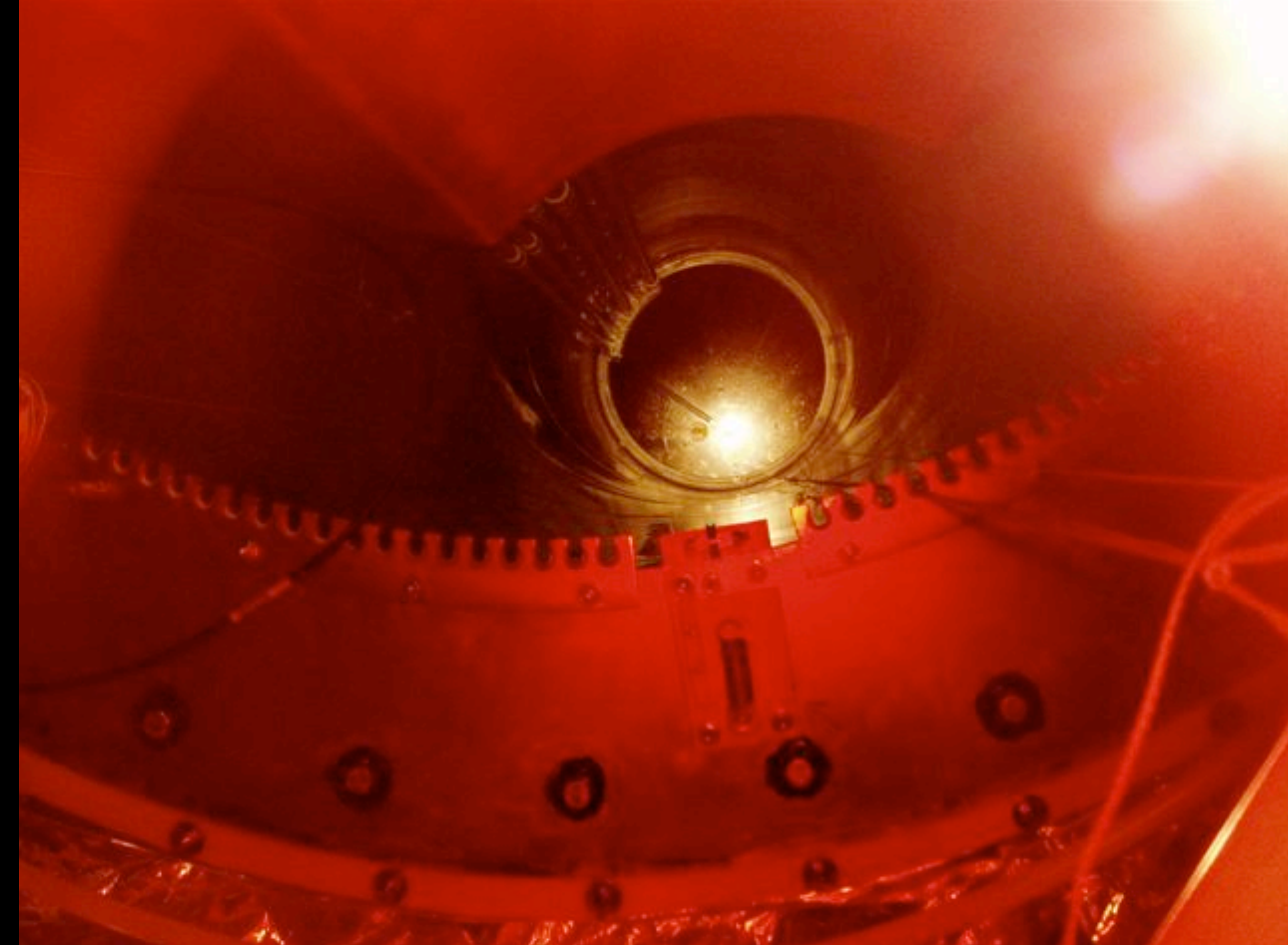
(6) Muon spallation at depth



SNOLAB

MINING FOR KNOWLEDGE

CREUSER POUR TROUVER... L'EXCELLENCE



...and the neutrino landscape

Twilight, again...

- SNO has completed its three-phase program, providing an accurate measurement on the mixing parameters of the solar sector.

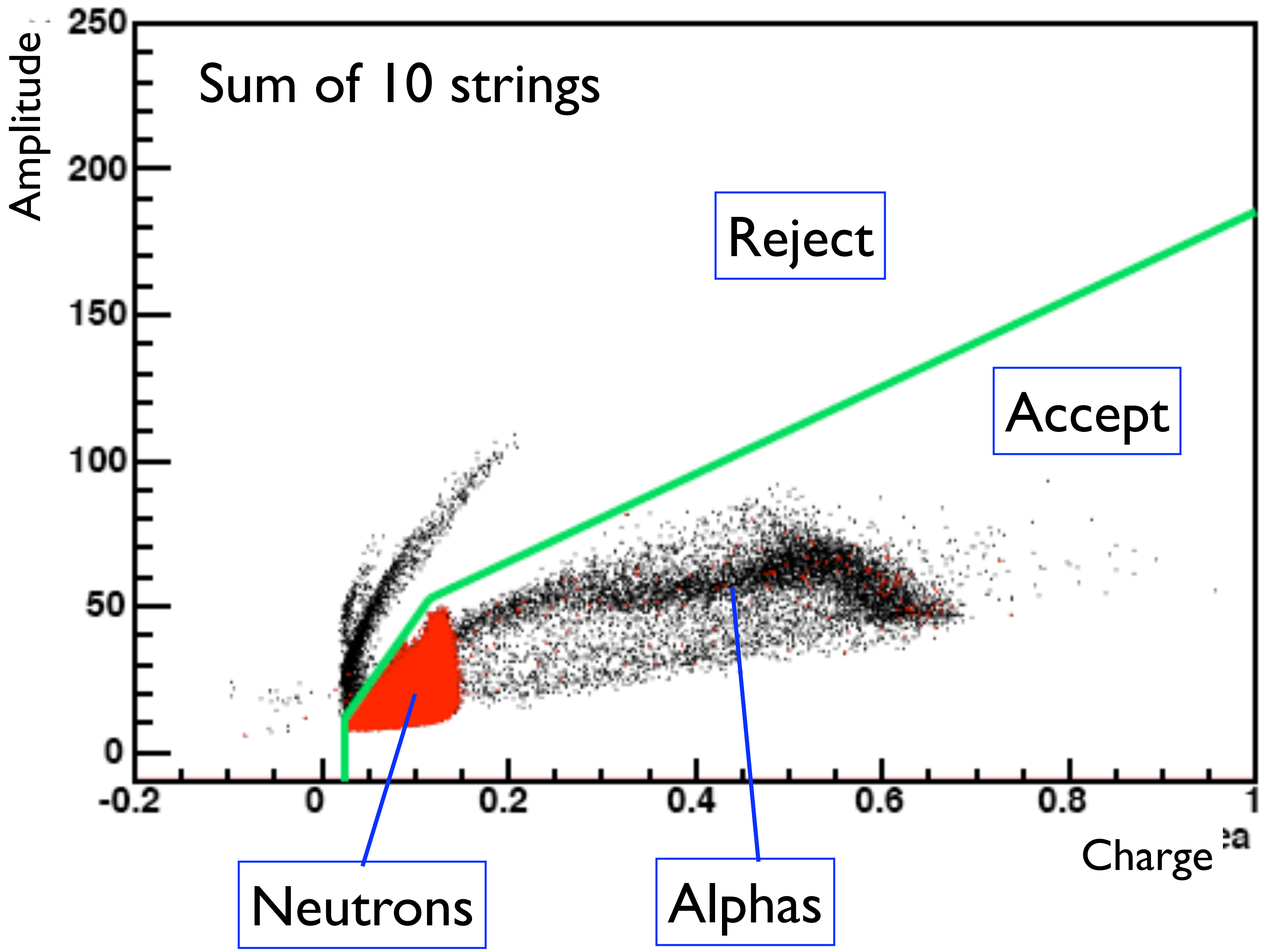
- The total flux rate consistent with solar models to date and provide a clear indication of neutrino mixing due to oscillations.

- More answers to be sought as a new day begins...


Fin
(Thank you for your time and attention)

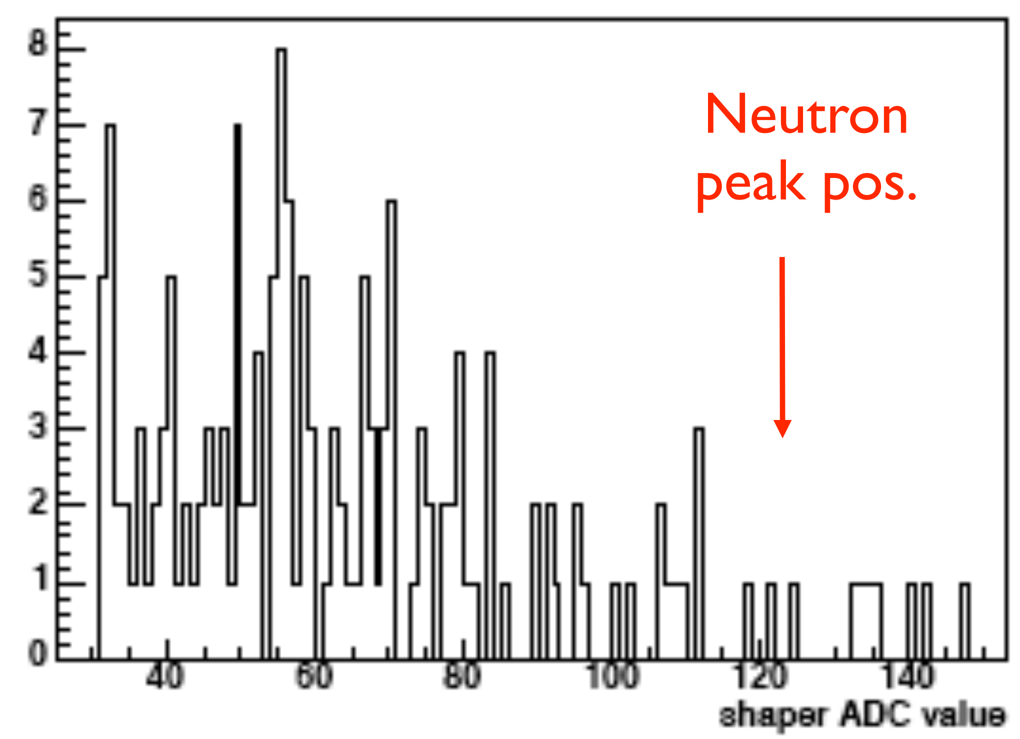

Extra Slides

Cutting instrumental events



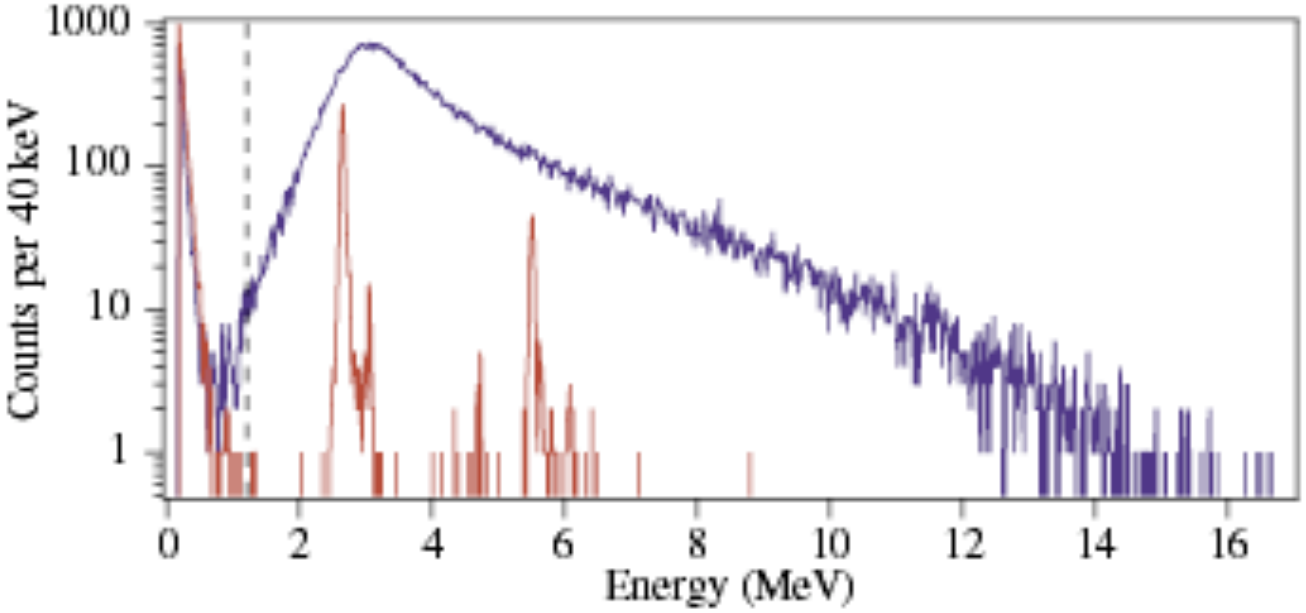
6 ^{3}He strings in total were dropped from the analysis.

Energy spectra of 2 strings showed instrumental events that could not be completely cut from neutron/alpha events.



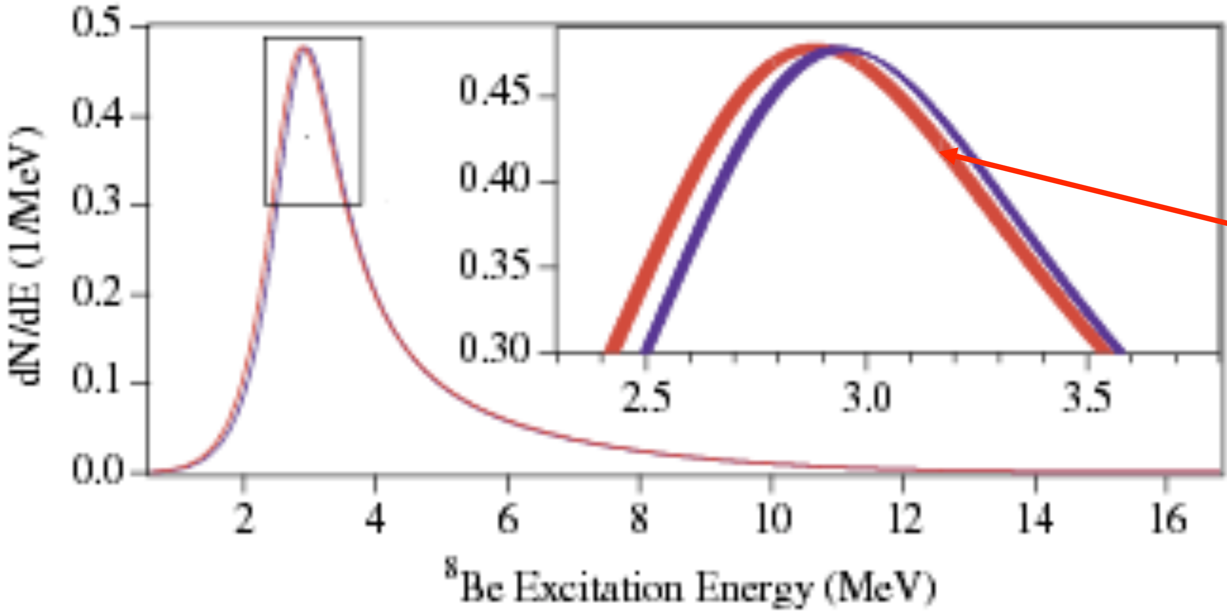
These strings were dropped and PDFs were added in the analysis to allow for such events to be present on other strings.

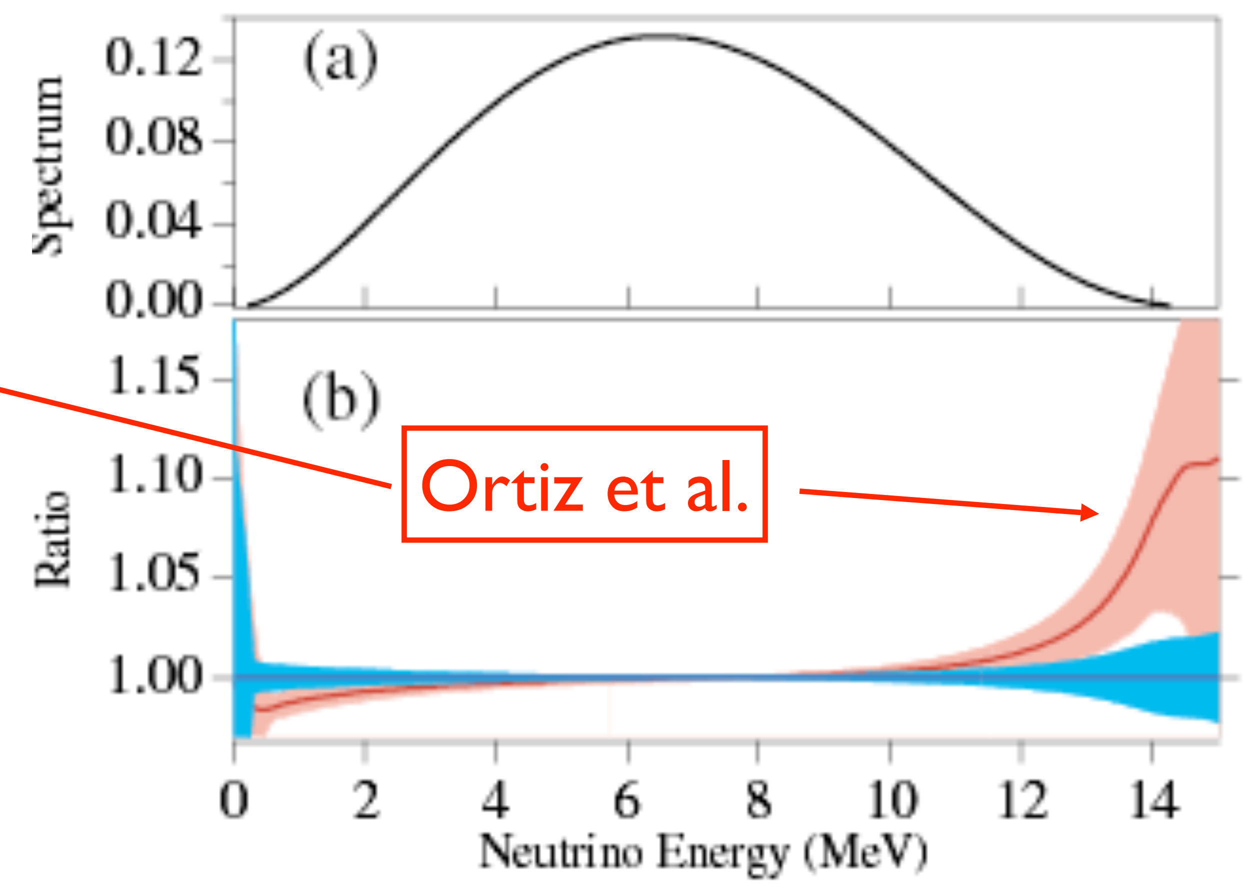
New Measurements of ^8B ν Spectrum



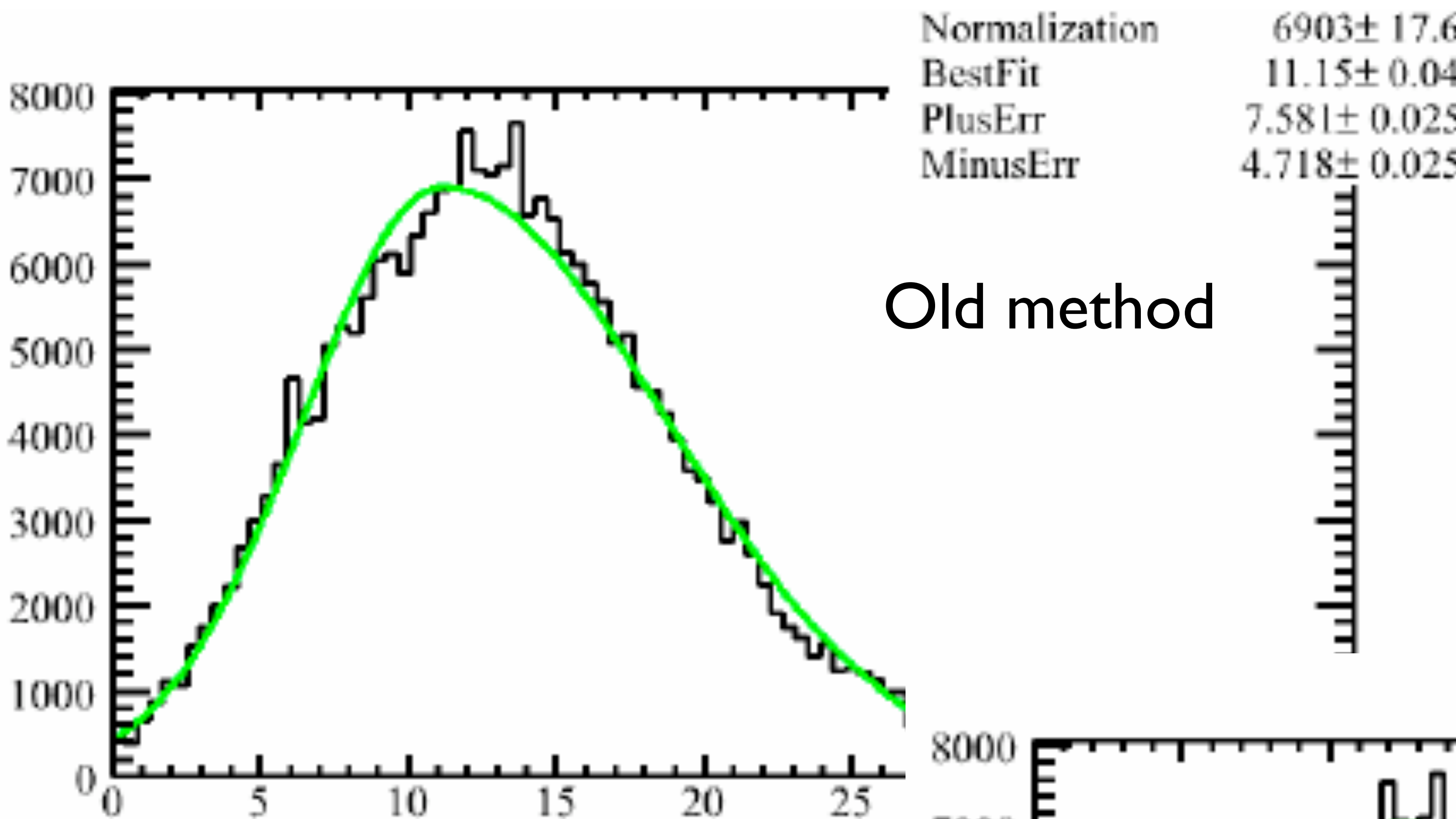
Winter, Freedman, et al. PRL **91** 252501, NP A746, 311 (2004).

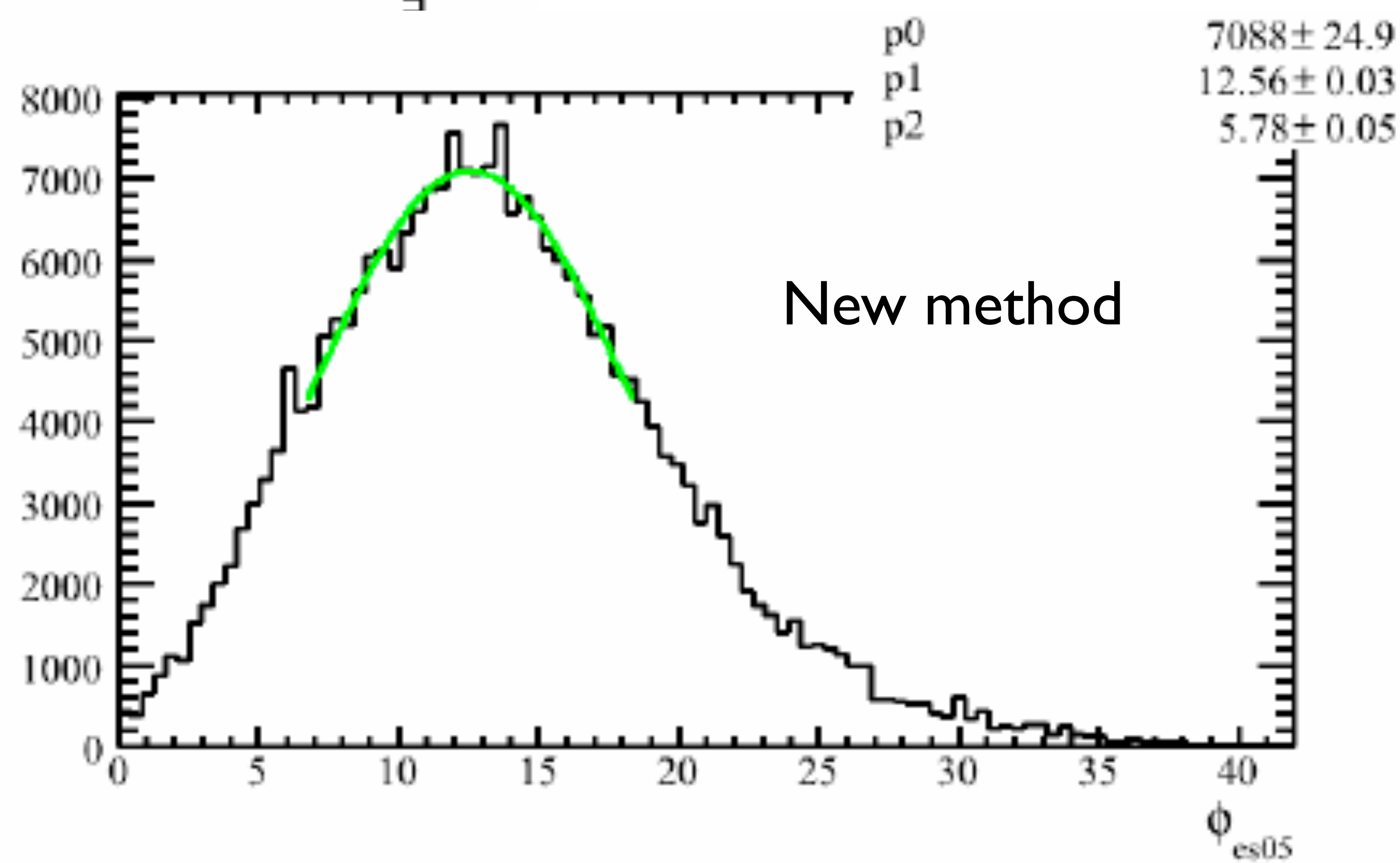
Bhattacharya et al. PRC **73**:055802,2006

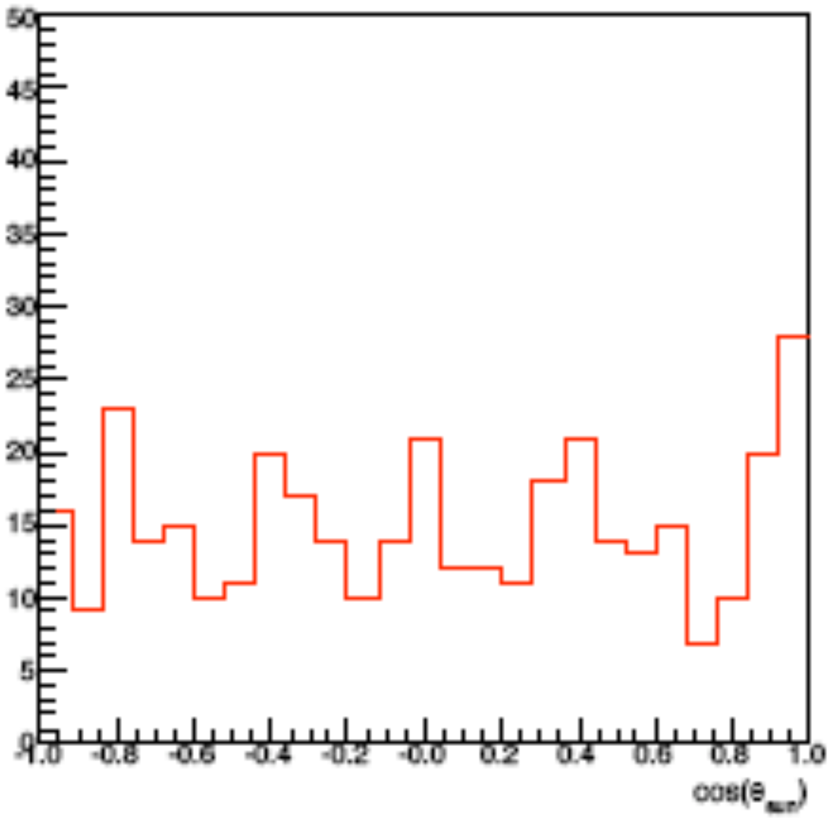




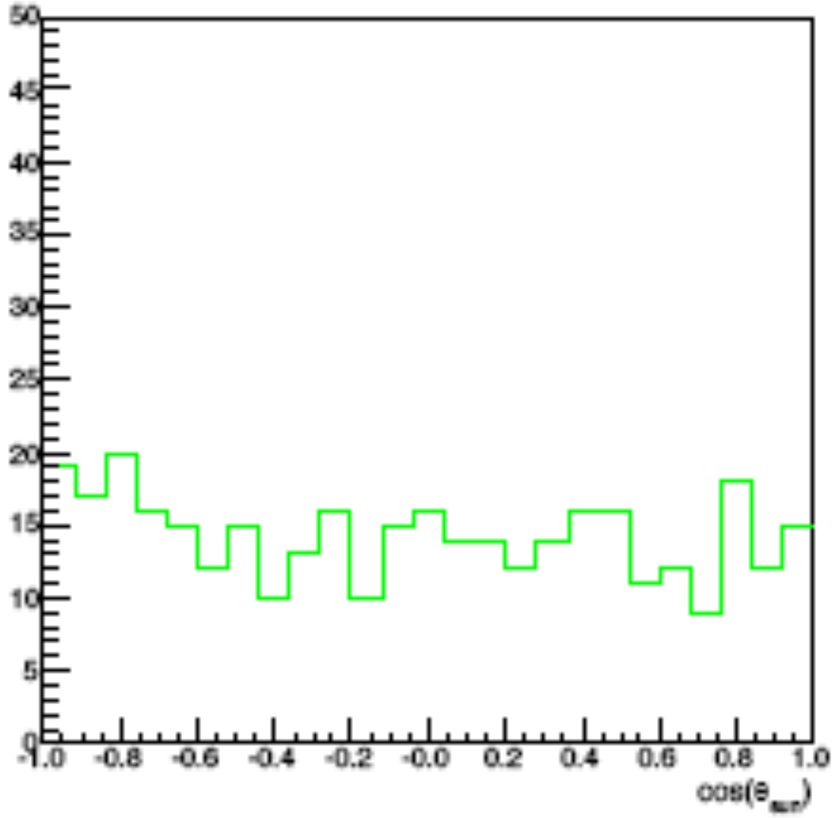
Change in parameterization for ES fit



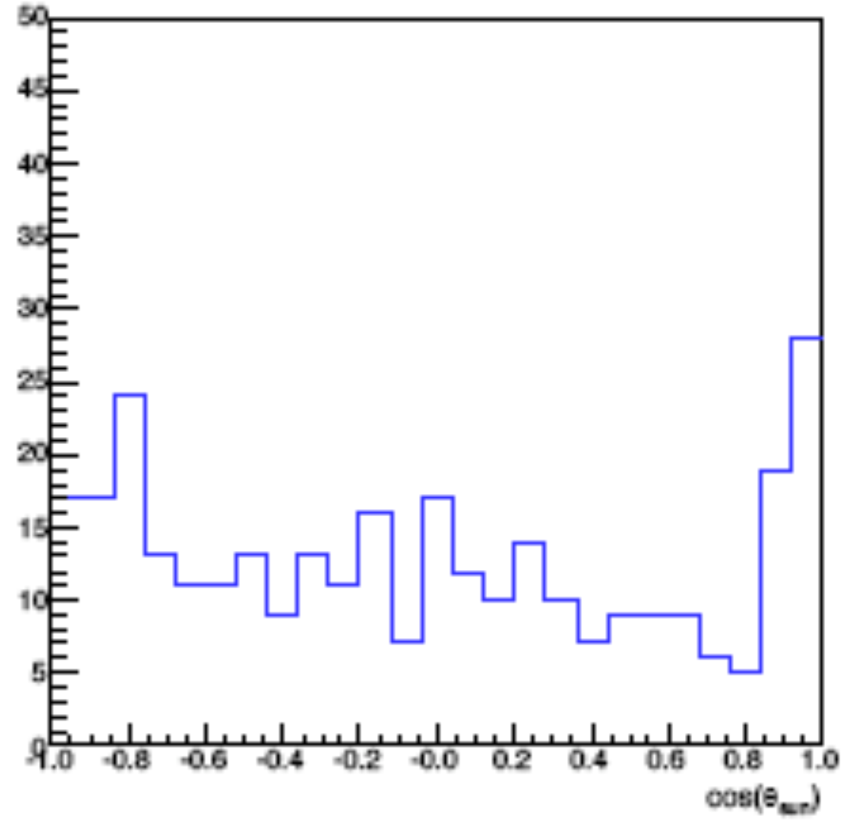




6.0 - 6.5 MeV

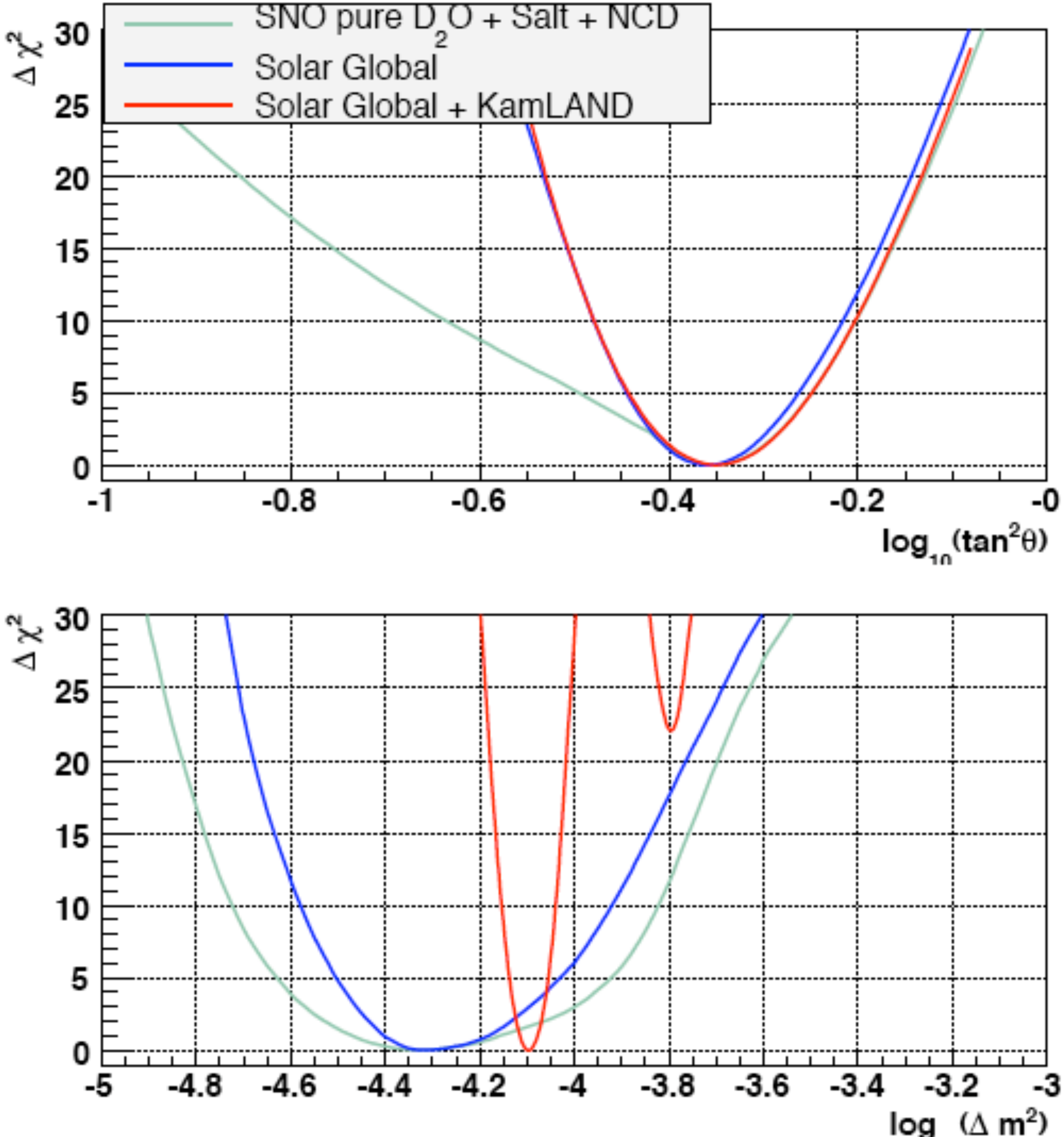


6.5 - 7.0 MeV



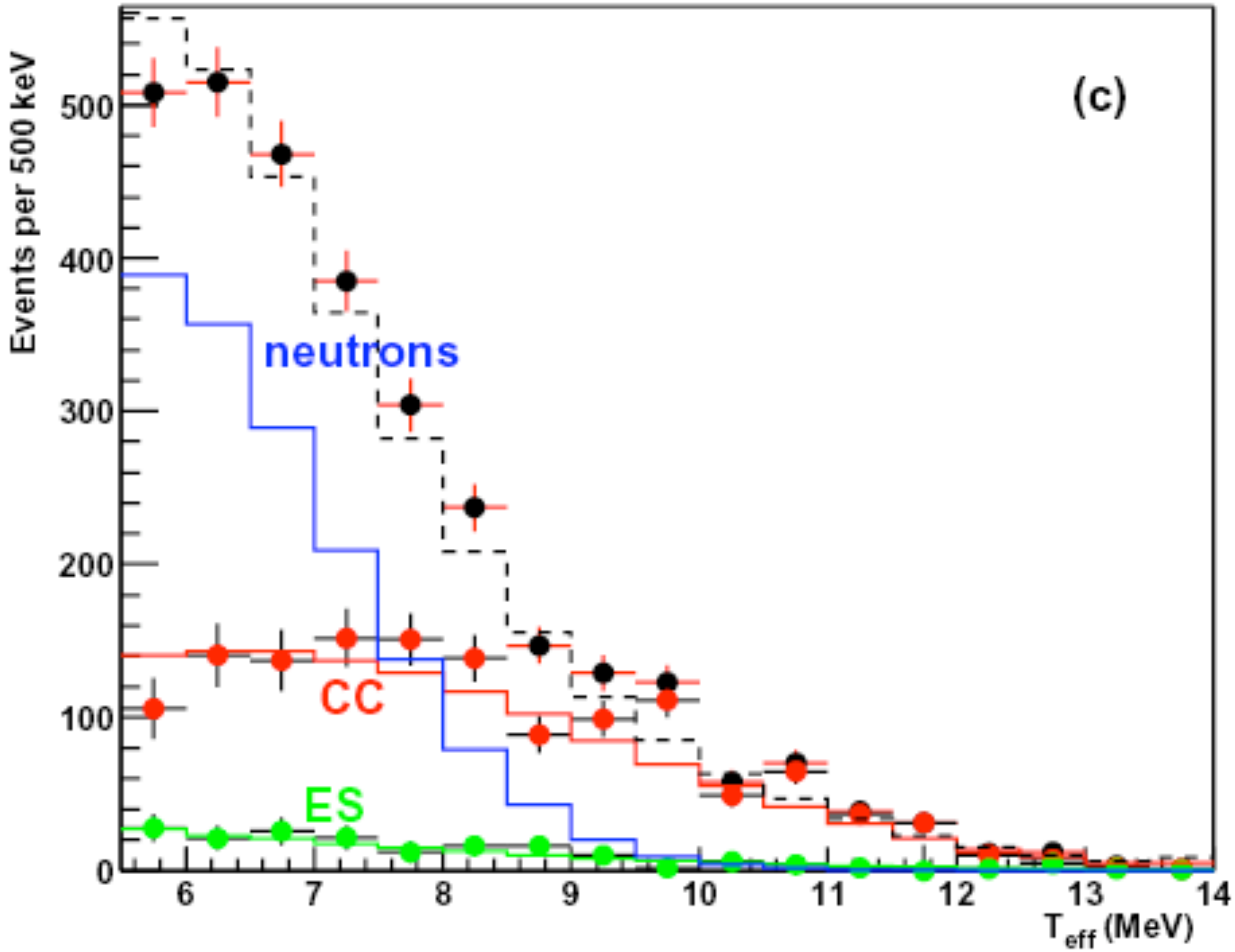
7.0 - 7.5 MeV

Angular distributions for ES in 3 Energy bins



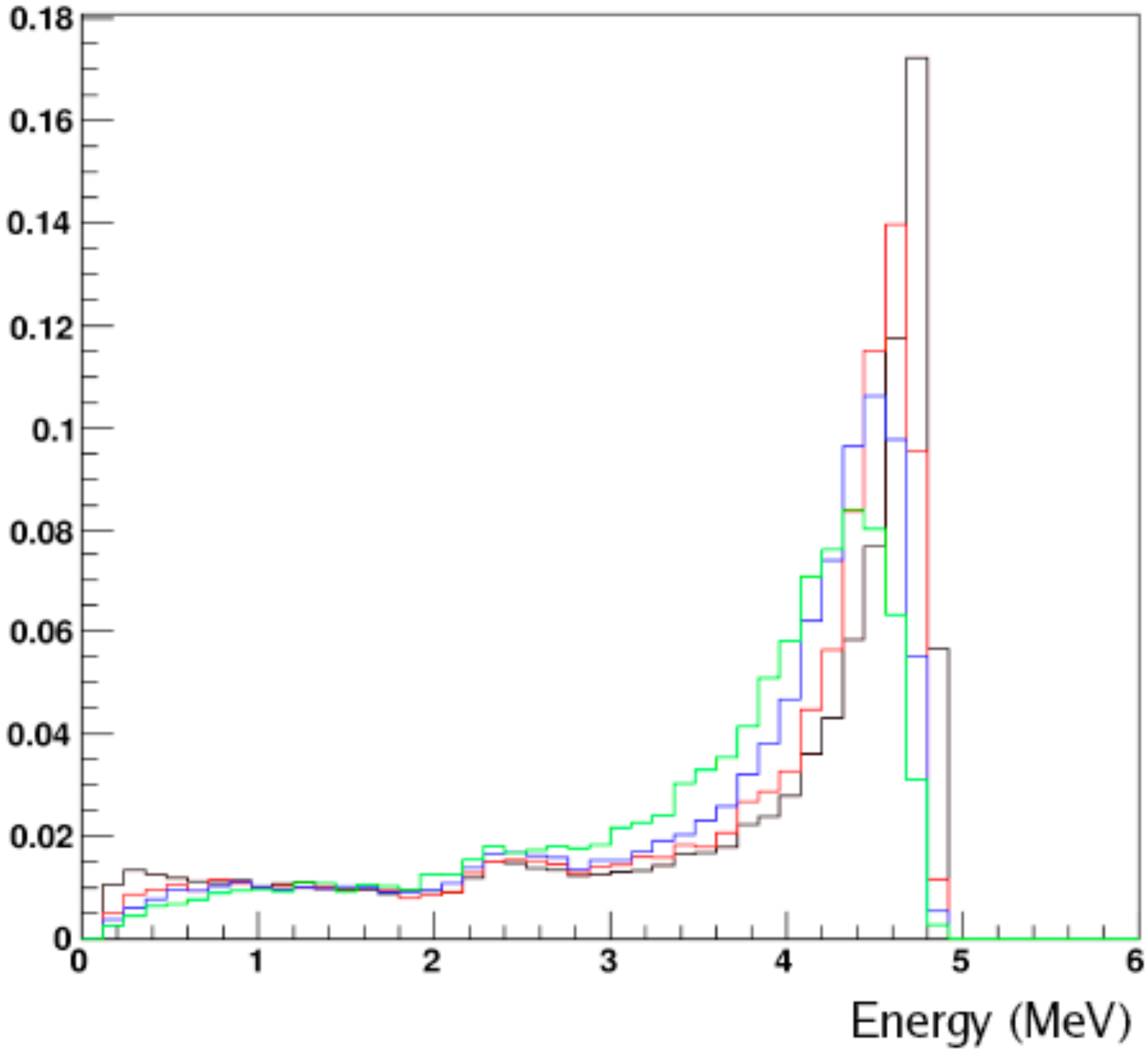
SNO pure D_2O + Salt + NCD
Solar Global
Solar Global + KamLAND
$\Delta\chi^2$
30
25
20
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
-0
$\log_{10}(\tan^2\theta)$
$\Delta\chi^2$
30
25
20
15
10
5
0
-5
-4.8
-4.6
-4.4
-4.2
-4
-3.8
-3.6
-3.4
-3.2
-3
$\log_{10}(\Delta m^2)$

Energy spectra, salt phase



Electron kinetic energy

Energy distribution assuming an embedded Po profile



Assume exponentially decreasing 210Po concentration inside nicke

Black: Surface Po
Red: 0.1 microns
Blue: 0.25 microns
Green: 0.5 microns

Muon "Calibration" at SNO

- No direct calibration exists to verify accuracy and precision of muon reconstruction algorithms.

- An external muon tracking system created and installed underground in order to provide an independent "calibration" of SNO's muon reconstruction.

- MIT lead effort for refurbishing, testing, installing, and analyzing data taken by the muon tracker:

    1) *Successful run underground, collecting 96 live days of data.*

    2) *Data analysis complete. Provides good check on muon tracks; consistent with projected expectations.*

    3) *Could not have been possible without support from Bates R&E Center.*

External Muon Counters tested at Bates Laboratory

External Muon Counters during underground installation.